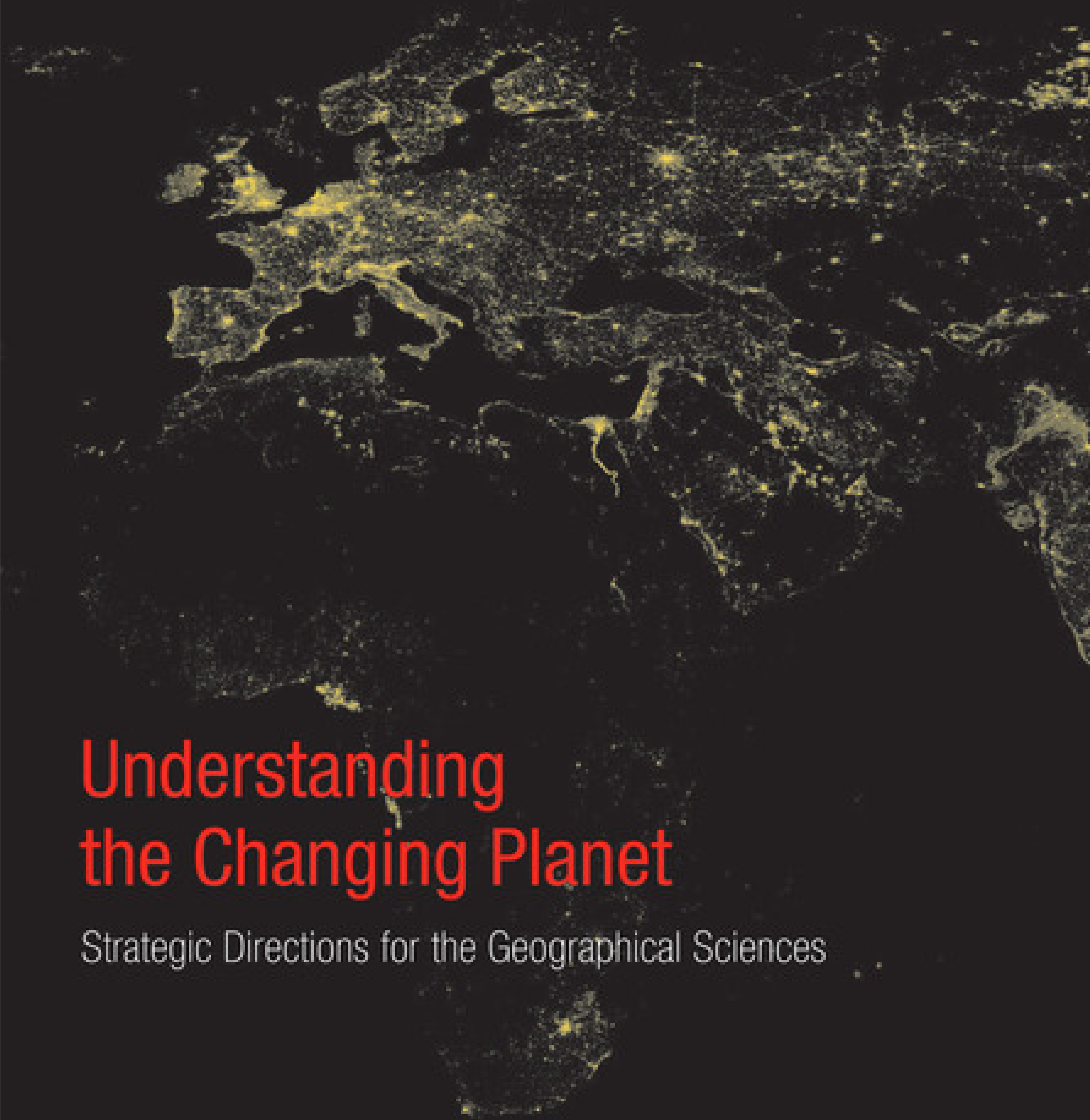

Understanding the Changing Planet

Strategic Directions for the Geographical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Understanding the Changing Planet

Strategic Directions for the Geographical Sciences

Committee on Strategic Directions for the Geographical Sciences in the Next Decade

Board on Earth Sciences and Resources

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

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International Standard Book Number-13: 978-0-309-15075-0
International Standard Book Number-10: 0-309-15075-2
Library of Congress Catalog Number: 2010926480

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

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Preface

We are living in an era of receding glaciers, accelerating loss of species habitat, unprecedented population migration, growing inequalities within and between nations, rising concerns over resource depletion, and shifting patterns of interaction and identity. These phenomena are changing Earth's geography—altering the character and organization of the planet's surface and the relationships that exist among its peoples and environments. At the same time, we are in the middle of an explosion in the availability and use of geographical information. From the screens of our personal computers to the dashboards of our cars, spatial information abounds. Geographic information systems (GIS)—and the analytical tools for using these systems wisely—now play a fundamental role in the provision of emergency services, transportation and urban planning, environmental hazard management, resource exploitation, military operations, and the conduct of relief operations. In the years ahead, geographical tools and techniques will be of vital importance to the effort to monitor, analyze, and confront the unprecedented changes that are unfolding on Earth's surface

The foregoing circumstances explain why Stanford ecologist Hal Mooney has suggested that we are living in "the era of the geographer"[1]—a time when the formal discipline of geography's long-standing concern with the changing spatial organization and material character of Earth's surface and with the reciprocal relationship between humans and the environment are becoming increasingly central to science and society. One significant marker of the relevance of geographical analysis is the growing number of scientists from other disciplines who employ geographical concepts and techniques in their work, including archaeologists, economists, astrophysicists, epidemiologists, biologists, geologists, landscape architects, and computer scientists. Their collective work has engendered a transdisciplinary geographical science. Understood in these terms, geographical science is not restricted to the discipline of geography; many geographers are involved, but increasingly so are individuals from other scientific fields and professions. To be a geographical scientist is to be concerned with reciprocal links between people and nature, as well as the spatial analysis and representation of the flows of mass, energy, people, capital, and information that are shaping, or have shaped, the evolving character of Earth's biophysical and human environment.

This assessment of strategic directions for the geographical sciences reflects the rapid growth of the geographical sciences and the urgency and importance of their applications. What are the most important geographical questions that deserve attention, and what are some of the most promising geographical approaches and analytical tools for tackling those questions? How can we mobilize a community of scientists to develop and use geographical perspectives and tools most effectively to contribute to the effort to understand and respond to a changing planet? These questions are at the heart of this report. Geographical approaches and techniques alone are not sufficient to address the sweeping changes that are remaking the

[1]Personal communication between Hal Mooney and Tom Wilbanks (verified February 12, 2009).

planet, but concepts and tools of the geographical sciences are essential components of the multidisciplinary task of unraveling the complexities of the changes Earth is confronting.

Geographical inquiry encompasses approaches ranging from the scientific to the humanistic, and this report's concern with the former end of the spectrum should not be seen as an effort to devalue nonscientific approaches, for the latter have fostered valuable insights into the geographical diversity of the planet and the human–environment dynamic. Rather, the focus on the geographical sciences comes in response to the National Research Council (NRC) of the National Academies' charge to assess the ways in which the community of geographically oriented scientists can effectively contribute to an understanding of the changes that are remaking the planet. In approaching its work, the committee that produced this report did not adopt a narrow definition of science, however. Instead, the committee evaluated various research endeavors that seek to advance applied and theoretical understanding based on the systematic analysis or assessment of empirical data and information.

This report is substantially different from previous NRC assessments focused on geographical research. Earlier studies focused on the character and perspectives of the discipline of geography (NRC, 1965; Taffe et al., 1970). More recently, *Rediscovering Geography* (NRC, 1997) sought to highlight what the discipline of geography had to offer at a time of rapidly rising interest in geographical ideas and to consider how geography might respond to that interest. That report was written principally "for the broad audience that is curious about geography's new place in a national spotlight" (NRC, 1997: 15).

This report, in contrast, is written against the backdrop of the emergence of a rapidly growing, interdisciplinary community of scientists that is drawing on a variety of geographical perspectives and techniques. The approaches that these geographical scientists employ include spatial analysis (often making use of GIS and related technologies), remote sensing, geographical visualization, numerical and analytical modeling, and deductive analysis based on spatial data and assessments of linkages among and between places. The central concern of this report is to assess how the array of approaches and techniques of the geographical sciences might be most effectively deployed in the effort to address major social and environmental questions. It is important to emphasize that the goal of the report is not to provide an overview of the geographical sciences or to offer an analysis of successes and challenges. Instead the goal is to elucidate key contributions the geographical sciences can make to the task of confronting some of the most pressing, contemporary large-scale scientific questions of the day.

The audience for the report, then, is twofold. On the one hand, it is written for researchers and scholars in a position to develop and advance the geographical science enterprise over the coming decade. On the other hand, it is aimed at scientifically literate people, including policy makers, who can benefit from an understanding of what the geographical sciences have to offer and who can help sustain and promote geographically grounded efforts to understand life on Earth in the 21st century.

In developing this report, the committee relied on NRC studies, other published reports and literature, and the experience and expertise of its members. The committee also solicited input from the broader community in three ways: first, in the form of presentations at the committee's open meetings; second, in a public panel session at the annual meeting of the Association of American Geographers (AAG); and third, from a Web-based questionnaire written by the committee, designed to gather community input on the committee charge. The committee used the community input to shape its discussion of potential research questions, and the research questions that resulted reflect the themes of the input.

The committee held three open meetings. The first was in Washington, D.C., at the National Academy of Sciences, where the committee heard from the sponsoring agencies and organizations, reviewed its task, and charted a course for the study. The second meeting was in Irvine, California, at the Beckman Center, where the committee heard presentations from invited guests and reviewed the community input it had received. Between the first and second meetings, the committee held its public panel session at the AAG meeting, which consisted of seven invited presentations (see Appendix C) and a question-and-answer session with the audience. The public panel session speakers spanned the range of the geographical sciences and were invited for their

expertise as well as their broad thoughts on the study charge. The committee held its third meeting in Woods Hole, Massachusetts, at the Jonsson Center, where it reviewed and discussed the draft research questions. The fourth and final meeting was a closed meeting at the University of California, Los Angeles, where the committee reviewed and finalized the draft report.

The committee is grateful for the input it received. As broad as the committee's expertise was, it could not expect to cover every area of importance to the report. As a result, the committee requested contributions from several researchers to key areas of the report: Yuko Aoyama, Michael Emch, Colin Flint, Geoffrey Jacquez, John Logan, W. Andrew Marcus, Sara McLafferty, and Joseph Oppong. The committee also would like to thank the individuals who made presentations at committee meetings and the AAG panel session: Tom Baerwald, Patrick Bartlein, Daniel Edelson, Mark Ellis, Cindy Fan, Rachel Franklin, Geoffrey Jacquez, Bruce Jones, David Maguire, Susanne Moser, Laura Pulido, Doug Richardson, David Rigby, Paul Robbins, Chris Shearer, Eric Sheppard, Daniel Sui, and Ken Young. The committee also received many responses to its Web-based questionnaire and would like to thank the following individuals for their input, as well as those who contributed anonymously: Tony Abbott, John Agnew, Sharmistha Bagchi-Sen, Oliver Belcher, Denise Chavez, Anne Chin, Kevin Czajkowski, Bernadette de Leon, Martin Doyle, Steven Driever, Stuart Elden, Philippe Foret, William Graf, Carol Harden, John Harrington, Jr., Douglas Herman, John Hatzopoulos, Marlene Jackson, Daryl Jones, Gerry Kearns, Joseph Kerski, Miles Logsdon, David Maguire, Richard Marston, Patricia McDowell, Amy Mills, Jarlath O'Neil-Dunne, David Paschane, Jonathan Phillips, Chris Pringle, Jeffrey Smith, Seth Spielman, Dawn Youngblood, and Paul Zellmer.

Finally, the committee and I are deeply grateful to staff members of the Board on Earth Sciences and Resources of the NRC for facilitating the study from inception to conclusion. We are particularly indebted to our initial study director, Caetlin Ofiesh, who was a constant source of help and encouragement during the preparation of the first draft of this report. We are also grateful to Ms. Ofiesh's successor, Mark Lange, who helped to bring this study to completion. Our study directors were ably assisted by Jared Eno and Jason Ortego, who provided invaluable assistance on a range of research and editing matters. We are also grateful for the administrative assistance of Tonya Fong Yee. Finally, we would like to express our gratitude to Tony de Souza, the Director of the Board on Earth Sciences and Resources. His commitment to this study was evident throughout the process, and we all benefited from his regular participation in our deliberations.

Alexander Murphy, *Chair*
February 2010

Acknowledgments

This report was greatly enhanced by input from participants at the workshop and public committee meetings held as part of this study. These presentations and discussions helped set the stage for the committee's fruitful discussions in the sessions that followed.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

John Agnew, University of California, Los Angeles
Bernard Bauer, University of British Columbia Okanagan, Kelowna, British Columbia, Canada
Anthony Bebbington, University of Manchester, United Kingdom
Maeve Boland, Colorado School of Mines, Golden
Patricia Gober, Arizona State University, Tempe
Gerard Rushton, University of Iowa, Iowa City
Billie Turner, Arizona State University, Tempe

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. William A.V. Clark, University of California, Los Angeles, and Dr. Farouk El-Baz, Boston University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

Increasing consumption, a growing and more mobile human population, and climate change are transforming the planet's surface, creating challenges that scientists and policy makers struggle to understand and address. Yet this era of change is also a time of geographical innovation. In recent years, a rapidly expanding interdisciplinary community of scientists has drawn on new geographical concepts, tools, and techniques to advance understanding of topics such as environmental change, sustainability, globalization, and population dynamics. As a result, geographical ideas and information have become increasingly central to science, as well as to planning, environmental management, and policy making. Dynamic maps and imagery of Earth's surface are now essential tools for emergency responders, transportation workers, and urban planners, and new user-friendly geographical technologies, such as Global Positioning System (GPS) tools and online maps, are becoming a part of daily life.

Many of the central challenges of the 21st century are tied to changes to the spatial organization and character of the landscapes and environments of Earth's surface as populations move, natural resources are depleted, and climate shifts. Research in the geographical sciences has the potential to contribute greatly to efforts to monitor, analyze, and prepare for these changes. Technological developments and changing research priorities have inspired the rapid growth of the geographical sciences over the past two decades. Moving beyond geography alone, economists, biologists, epidemiologists, geologists, computer scientists, and others now contribute to the geographical sciences—investigating the links between people and nature, and the flows of mass, energy, people, capital, and information that are shaping Earth's evolving environment. New technologies such as remote sensing systems have enhanced access to high-resolution, near real-time data, and geographical information systems (GIS), GPS, and geospatial visualization have facilitated the processing, analysis, and representation of geographical data. These technologies are used in contexts from the workplace to everyday life, and they have profound implications for information management, governance, commerce, and travel. At the same time, growing concern about human alteration of the environment and the impacts of globalization, resource depletion, and environmental sustainability have fostered tremendous interest in climate change, land-cover change, watershed restoration, migration, global inequality, and geopolitical conflict. Investigation of all of these phenomena can benefit from geographical research.

Despite the potential of recent advances in the geographical sciences, there is still much to be done to understand the changes that face Earth in the 21st century. Earth's surface has been in constant flux as physical systems and human societies have evolved, but the pace and extent of human-induced changes have reached unprecedented levels in recent decades. The massive, rapid changes unfolding on Earth's surface provide a logical starting point for considering strategic research directions in the geographical sciences, with the goal of understanding how Earth's surface is changing; where, why, and at what rate changes are occurring; and what the implications of those changes might be.

SCOPE AND PURPOSE OF THE REPORT

At the request of the National Science Foundation, the U.S. Geological Survey, the National Geographic Society, and the Association of American Geographers, the National Academies established a committee to determine how the geographical sciences can best contribute to science and society in the next decade through research initiatives aimed at advancing understanding of major issues facing Earth in the early 21st century.

> An ad hoc committee will formulate a short list of high-priority research questions in the geographical sciences that are relevant to societal needs. The questions will be written in a clear, compelling way and will be supported by text and figures that summarize research progress to date and outline future challenges.

The committee focused on impacts that are profoundly altering the human and the physical characteristics of Earth's surface, and considered how the geographical sciences could contribute to understanding and addressing these transformations. In keeping with the charge, the committee developed 11 high-priority research directions that have clear societal significance, are central to the core concepts of the geographical sciences, relate to the agendas of the larger scientific community, have a strong likelihood of being advanced in the next 5-10 years, and can be investigated using methods and sources of data that either currently exist or are expected to be readily available within the next few years.

The committee solicited input from the greater geographical science community to identify research priorities and the approaches, skills, data, and infrastructure necessary to advance research. After arriving at the strategic research questions, the committee outlined the societal significance of each question, discussed the contribution of the geographical sciences to the topic so far, and determined how future work could produce new insight.

STRATEGIC DIRECTIONS

The geographical sciences have the potential to improve understanding of the extent and causes of the changes unfolding on Earth's surface, to offer insight into the impacts of those changes, to promote the development of effective strategies in response to those changes, and to facilitate the documentation and representation of Earth's changing character. The order in which the strategic directions are presented reflects the movement from overarching issues of environmental change and sustainability to matters that bear on particular transformations unfolding in the socioeconomic, geopolitical, and technological arenas.

How to Understand and Respond to Environmental Change

1. How are we changing the physical environment of Earth's surface?
2. How can we best preserve biological diversity and protect endangered ecosystems?
3. How are climate and other environmental changes affecting the vulnerabilities of coupled human–environment systems?

Increasing human populations, urbanization, industrialization, and climate change have modified Earth's surface and depleted natural resources. Although previous research has documented shifts in climate, soil erosion, habitat loss, and water degradation, the human role in these changes is often inadequately understood, hindering abilities to predict the magnitude and timing of future change. Using paleoenvironmental data such as tree rings and fossilized pollen, geographical scientists are developing reconstructions of long-term environmental history to learn about fluctuations in climate and Earth's physical systems through time. Geographical scientists are using GIS, remote sensing, and geospatial visualization to analyze alterations to physical processes and patterns over time, and to figure out the relative contributions of the physical and the human to environmental change. A more complete understanding of both natural and human-made changes to Earth's surface, the distribution of species and genetic diversity, and the varying vulnerabilities of different ecosystems to environmental change will be fundamental to environmental science, hazards management, and ecological restoration, and can guide policy decisions aimed at promoting environmental sustainability.

How to Promote Sustainability

4. How and where will 10 billion people live?
5. How will we sustainably feed everyone in the coming decade and beyond?
6. How does where we live affect our health?

Earth's population is projected to peak at 8 to 12 billion people by 2050, with most population growth in urban areas. Many cities will struggle to accommodate rapidly increasing populations, and the spread of cities into rural areas will alter biogeochemical cycles, hydrological systems, climate, wildlife habitat, and biodiversity. Research on the changing geographical distribution of populations, the processes shaping different settlement forms, and the sustainability challenges facing an increasingly urbanized population are critical to understanding the challenges facing a more crowded world. Ensuring the availability of food resources to feed Earth's expanding population will be one of those challenges. Because starvation currently occurs not because of global food scarcity but because of unequal geographical circumstances and inefficient or unfair food distribution systems, meeting the critical challenge of feeding 10 billion people will require a better understanding of geographical influences on agricultural production and distribution systems and on changing food consumption preferences. Access to health care will also be stretched by an expanding, increasingly mobile population, and standards in the treatment and prevention of illness will vary according to location. Using spatial analysis, GIS, and spatially explicit models of disease spread, the geographical sciences can advance understanding of the impacts of globalization, migration, environmental circumstances, land use, economics, and government policy on health and the spread of infectious diseases. Analysis of disease and health care patterns through the course of people's lives is fundamental to understanding both disease behavior and the varying vulnerabilities of different populations. This information will be essential to developing policies that promote greater human well-being around the globe.

How to Recognize and Cope with the Rapid Spatial Reorganization of Economy and Society

7. How is the movement of people, goods, and ideas changing the world?
8. How is economic globalization affecting inequality?
9. How are geopolitical shifts influencing peace and stability?

From human migration to the movement of freight, global mobility has increased over the past several decades, affecting transportation, communication, the economy, and even patterns of political conflict. There is a pressing need to understand the causes and consequences of increasing mobility, mobility differences from place to place, and the relationship between virtual (as in the Internet and other media) and physical mobility through in-depth assessments of developments in individual places and more spatially extensive studies that use GIS and geospatial information. Globalization is also exacerbating economic disparities in many places, raising concerns about the plight of the needy and social unrest. Geographical research elucidating patterns of inequality and the processes producing those patterns at different spatial scales can shed light on the inequality impacts of the changing socioeconomic environment, as well as the links between poverty and consumption patterns. The geopolitical framework that dominated the post-World War II era has also come apart in the face of economic and social upheaval, raising the need for expanded research on the territorial agendas of influential governments and groups, the changing significance of boundaries, and the role of resource scarcity in cooperation and conflict.

How to Leverage Technological Change for the Betterment of Society and Environment

10. How might we better observe, analyze, and visualize a changing world?
11. What are the societal implications of citizen mapping and mapping citizens?

Since ancient times, observation, mapping, and representation of Earth's surface have been integral to geographical research, and remain central to the modern

geographical sciences today. Web sites that provide geographical information have become a critical part of daily life, empowering citizens as both the sources and subjects of mapping, but the explosion of geographical information has raised significant concerns about individual privacy. Recent advances in geographical tools and technologies to observe, analyze, and visualize the changes shaping the human and physical features on Earth's surface will be critical to answer the research questions in this report and to advance the geographical sciences. However, new approaches are also needed both to take advantage of the ability and willingness of nonspecialists to provide geographical information and to protect their privacy.

MOVING FORWARD

The 11 strategic directions in this report illustrate the great potential of the geographical sciences to address fundamental challenges facing science and society in the early 21st century. Given the extent and magnitude of the geographical transformations currently unfolding, it will be imperative to understand why changes happen in particular places. Although rapid progress has been made in geographical research in recent years, moving forward will require efforts to expand the scope and reach of geographical research. Achieving this goal will necessitate advances in research infrastructure, training, and outreach efforts. For example, most progress in the geographical sciences to date has been the result of independent research initiatives, but large-scale collaborations between researchers with diverse areas of expertise are needed to address many of the challenges facing Earth in the 21st century. Training the next generation of geographical scientists will require an updated curriculum to promote geographical understanding, spatial thinking, and geographical research skills, and to teach students how to make use of recent technological advances. Outreach is needed to inform policy makers, administrators, media figures, and others of the potential offered by the geographical sciences, and to foster links between the geographical science community and the general public. The committee envisions that the research priorities outlined in this report will lead to an increasingly sophisticated, well-organized, and powerful geographical science, which will serve as a foundation for a broad spectrum of scientific research, inform policy decisions, and enable citizens to understand and critique the geographical technologies that play an increasingly important role in everyday life.

Part I

Introduction

Introduction

On August 29, 2005, Hurricane Katrina struck the city of New Orleans, Louisiana, and adjacent coastal areas. Strong winds and intense rain raced up the Mississippi River Delta with the eye of the storm immediately east of New Orleans over Lake Pontchartrain (Figure 1). Westward wind rotation forced the surface of the lake toward the city. The massive pulse of energy and water, albeit not extreme by historical hurricane standards, resulted in the failure of multiple levees, which in turn overwhelmed pumping capabilities and produced widespread flooding. The devastation included some 1,500 deaths, $40-50 billion in physical damages, and the largest forced migration of residents in U.S. history, with approximately 410,000 evacuees still scattered across the country as of October 2006 (Groen and Polivka, 2008).

The meteorological and engineering components of the Katrina disaster help us appreciate what happened. Yet bringing the analytical strengths of the geographical sciences to bear on the storm—situating it in the context of a set of evolving human and environmental circumstances near and far—is essential to understanding the larger causes and consequences of Katrina and to making effective plans for future disasters. The perspective adopted by the geographical sciences involves four dimensions.

First, the Katrina disaster was not an environmental event so much as it was a *human–environment* event. If the storm had encountered a differently organized landscape, then the impacts might have been less severe. A land-use planning process rooted in the geographical sciences would have produced a pre-Katrina New Orleans with a more extensive deltaic and wetlands buffer, with stronger levees and pumping systems, and with more robust evacuation plans for all neighborhoods. In short, coupled physical and human

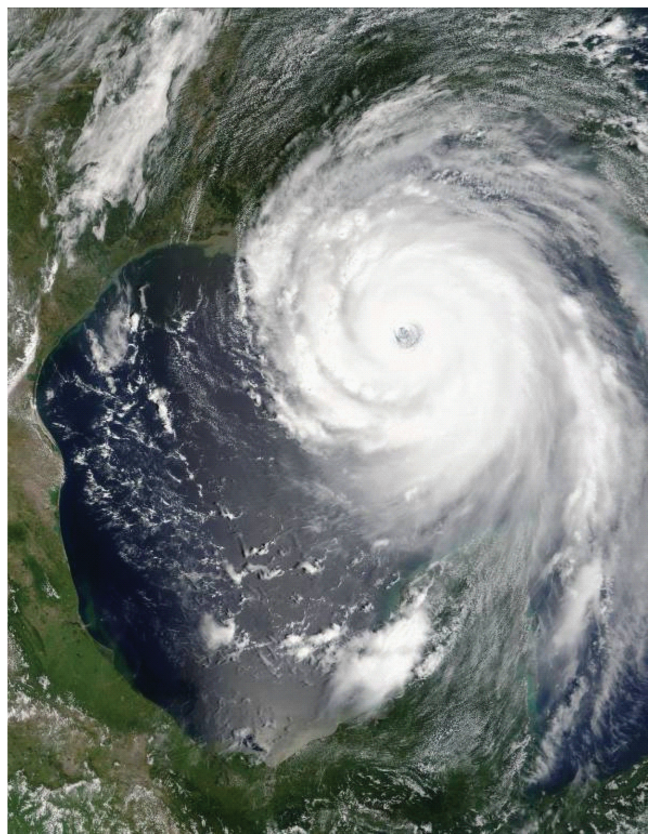


FIGURE 1 Image of Hurricane Katrina on August 28, 2005, from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the National Aeronautics and Space Administration (NASA) Terra satellite. SOURCE: Jeff Schmaltz, MODIS Rapid Response Team, NASA Goddard Space Flight Center.

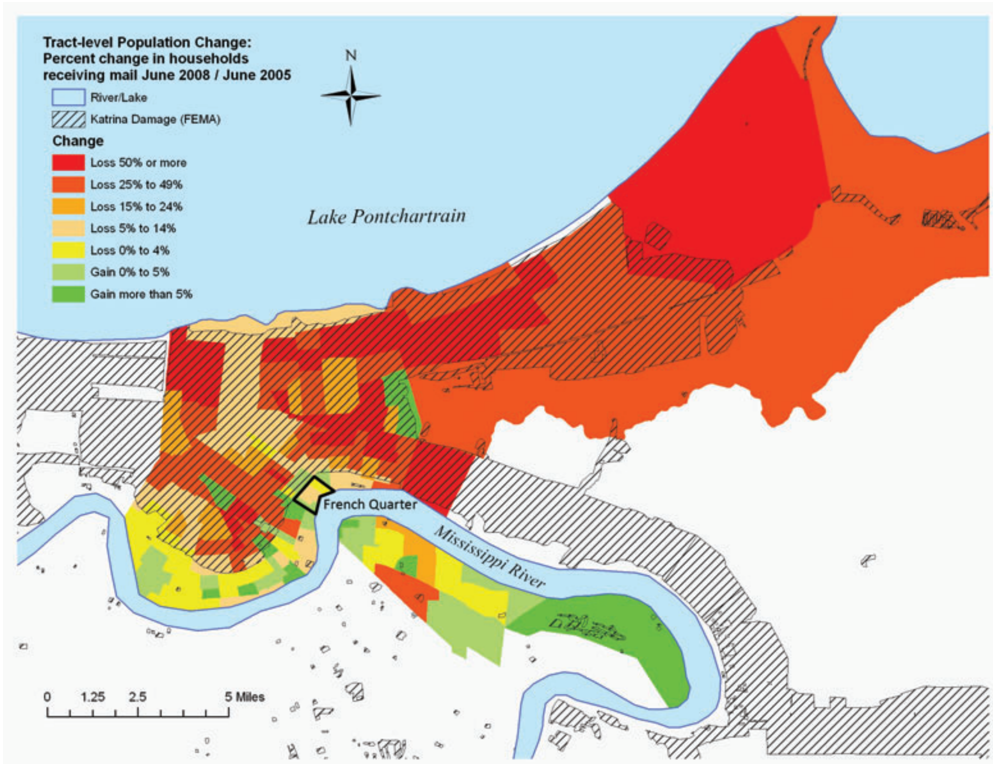


FIGURE 2 The percentage change in the number of households receiving mail from June 2005 to June 2008 in New Orleans Census tracts gives an estimate of changes in population, showing a complex spatial pattern of population gain and loss. SOURCE: American Communities Project, Brown University; mail receipt data from U.S. Postal Service, damage data from the Federal Emergency Management Agency.

processes,[1] rather than simply the physical storm itself, made the Katrina disaster what it was.

Second, the storm's impacts were not evenly distributed, but instead exhibited important *spatial variations and patterns*. Although many of the damaged New Orleans neighborhoods near Lake Pontchartrain have lost 25-50 percent or more of their pre-Katrina populations (Figure 2), other neighborhoods in the same area have registered much lower population losses, while some neighborhoods have even experienced population growth since the storm. Explaining such spatial variations and patterns requires understanding how past decisions and practices, including possible socioeconomic or racial biases, affected different places (e.g., Did policy differences between neighborhoods produce different impacts within the city of New Orleans? Why have some neighborhoods gained population since the storm?). A better understanding of such spatial relationships could help residents and decision makers anticipate and mitigate the human toll from the next storm.

Third, the processes that led to the Katrina disaster operated at *multiple and interlocking geographical scales*, meaning that processes that led to the outcomes were operating at different scales, with each process possibly affecting the others. Mapping Katrina's impacts at different geographical extents and resolutions highlights the potential for added insights when the same outcome is viewed at different scales. A Gulf Coast–scale map of county-level population change from 2005 (before the storm) to 2007 shows broad but nuanced patterns of post-Katrina population movement (Figure 3). In this map the localized pockets of modest population loss, and population gain, manifest in Figure 2 are not evident. By contrast, the regional view may provide insights that the finer-scale picture cannot provide, such as the areas where some of the displaced Gulf Coast residents may have moved—namely, areas north and west of the damaged areas. A geographical sci-

[1]Coupled physical and human processes are processes that are inextricably interrelated, so that the physical process cannot be understood without reference to the human process, and vice versa.

ence perspective would use this pair of maps to ask questions such as the following: Were the locations of population gain the product of Katrina out-migration, or of in-migration by people previously not resident in the region? What state-level policies, if any, were responsible for this pattern of population shifts, and did those policies and their effects vary by state? Did the emergency response effort by the Federal Emergency Management Agency contribute to some of the patterns apparent from the maps?

Fourth, understanding Katrina and the processes that led to its dramatic and yet uneven impacts requires *integrating spatial and temporal analyses*. Even though the historical context of urban development in New Orleans was responsible for some of the spatial variations in who was most adversely affected by Katrina and what areas were most able to recover quickly, there are other, less spatially and temporally proximate, contributing factors. Also responsible was a long-term commitment to agricultural development in the Mississippi River basin, which has involved massive hydroengineering projects and activities (e.g., dredging/channeling, damming, straightening, levee building), and agricultural reclamation policies, which together have contributed to significant loss of protective wetlands in the delta area by altering the natural sediment regime over hundreds of miles of one of the world's greatest rivers. Looking to the future, a better understanding of hurricane patterns over time in the Atlantic Ocean and the Gulf of Mexico can provide insight into how and why hurricanes happen, and help construct improved climate models that can facilitate planning for future storms like Katrina. Such forward-looking research is particularly important given the possible impacts of anthropogenic climate change, sea-level rise, and changing land-use patterns on the Mississippi River, its delta, and the Greater New Orleans region.

Geographical scientists use a suite of approaches and tools (e.g., mapping, geographic information systems [GIS], remote sensing, spatial statistics, modeling, deductive analysis drawing on sociospatial data) to provide insight into the forces that produce events such as Hurricane Katrina and to understand their

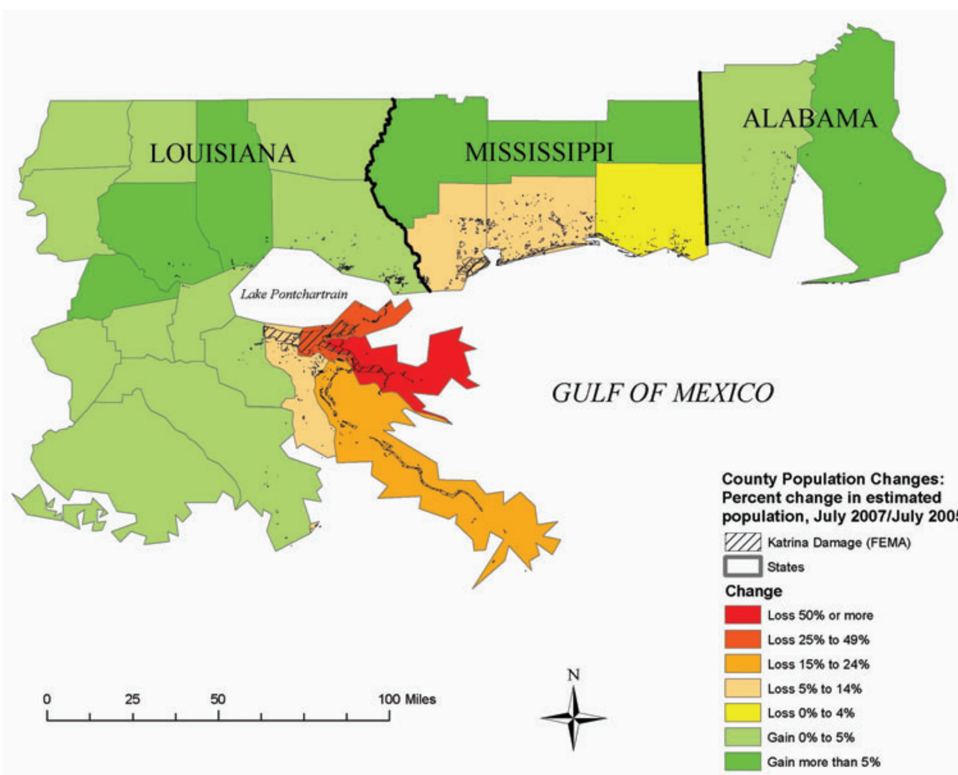


FIGURE 3 Mapping population changes for counties along a swath of the Gulf Coast illustrates broader spatial patterns of movement. This pattern influenced and was influenced by processes operating at multiple scales, such as the local, state, and regional (i.e., Mississippi Basin). SOURCE: American Communities Project, Brown University; population data from U.S. Census Bureau, damage data from the Federal Emergency Management Agency.

BOX 1
Geographical Science in Action During Hurricane Katrina

Geographical scientists played an important role in the response to Hurricane Katrina. Geographical scientists from Louisiana State University occupied the GIS desk in Louisiana's emergency operations center (EOC), mapping 911 calls, making recommendations for the best places to locate shelters, and processing imagery to show flood extent. One geographical scientist helped create the map that became the primary visualization used by the EOC to understand situation awareness—a Google Earth mashup[a] showing the flood extent on top of a three-dimensional image of New Orleans. Geographical scientists also used Google Earth to identify possible landing zones close to health facilities for search-and-rescue helicopter pilots and helped coordinate responses among agencies. In addition, they accompanied Red Cross Disaster Assessment Teams in the field, helping them understand and map residential changes in the wake of the hurricane.

[a]A mashup is a product that combines data from two or more sources into a new single product.

consequences for the Gulf Coast and beyond (see Box 1). The core concepts, methods, and tools of the geographical sciences are essential not only for assessing what happened, but also for asking what will become of New Orleans and surrounding areas, for evaluating alternative redevelopment scenarios, and for developing designs that will prevent a similar-scale disaster in the future.

EMPIRICAL AND METHODOLOGICAL APPROACHES OF THE GEOGRAPHICAL SCIENCES

Drawing upon the four core concepts described through the example of Hurricane Katrina, empirical work in the geographical sciences focuses on documenting, analyzing, and explaining (1) the location, organization, and character of physical and human phenomena on the surface of Earth and (2) the interplay of arrangements and processes, near and far, human and environmental, that shape the evolving character of places, regions, and ecosystems. These concerns, which have long been central to the discipline of geography, have recently been taken up by researchers in a range of disciplines who are interested in how the geographical configuration and interaction of different phenomena shape the evolution of places, environments, and societies. To cite only a few examples, spatial econometrics has emerged as a major subfield of economics, environmental studies programs with a focus on human impacts on the environment have sprung up in universities and research institutes across the country, a Spatial Pattern Analysis Program for Categorical Maps (FRAGSTATS) is increasingly used in ecological research, and geographical technologies[2] have come to play a central role in fields ranging from epidemiology to archeology.

The rapid growth of the geographical sciences over the past two decades is a reflection of both technological developments and changing research priorities. On the technological side, modern remote sensing systems have greatly enhanced the ability of the scientific community to access increasingly high-resolution, near real-time data on the operations of human and biophysical systems.[3] At the same time, a quartet of technologies—GIS, Global Positioning Systems (GPS), remote sensing, and geospatial visualization—have facilitated the processing, analysis, and representation of geographical data. It is only a modest exaggeration to say that these technologies are revolutionizing everything from the workplace to everyday life—with profound implications for information management, governance, commerce, and travel.

On the research front, growing concern about human alteration of the environment, the impacts of globalization, and resource depletion has fostered a great deal of scientific interest in climate change, land-cover change, watershed restoration, sustainability, migration, and global inequality. All of these matters raise fundamentally geographical questions. How are human and environmental systems linked,

[2]The adjective *geospatial* is increasingly used to refer to data about identified locations on Earth's surface, and the tools used to manipulate those data. As such it is essentially synonymous with *geographical*, which seems more appropriate in the context of this report.

[3]Note, however, that remote sensing provides far more data on biophysical systems than on human systems.

and to what effect? How do phenomena and process vary across the surface of Earth? How do developments at particular scales reflect and shape processes at other scales? How are systems evolving across space and time? These questions require researchers to wrestle with geographical concepts, and the new geographical technologies described above are often of great use in efforts to address them.

The effort to confront the foregoing questions has given rise to robust transdisciplinary research communities focused on coupled human–environment systems. It has also fostered a powerful conceptual engagement with spatial thinking—a constructive amalgam of concepts of space, tools of representation, and processes of reasoning (NRC, 2006). These developments make clear that the geographical sciences are about much more than simply mapping phenomena and describing variance across places. They are instead rooted in a concern with the interaction of phenomena and systems that were long treated as distinct (e.g., human and natural systems); an interest in investigating how spatial variance can help refine general theories or models, rather than simply being treated as something to be held constant; and a recognition that explaining patterns and processes on Earth's surface requires consideration of how they have evolved through time and are shaped by developments at different scales. In pursuit of such concerns, much research in the geographical sciences involves some combination of the following methodological approaches: collection, analysis, and visualization of spatially explicit data; investigation of the relationship between large-scale processes and local or regional outcomes; and landscape analysis.

Collection, Analysis, and Visualization of Spatial Data

Efforts to record, analyze, and display spatial information are central to much work in the geographical sciences. Maps showing the changing distribution of diseases point to environmental factors that can make people sick (e.g., Jacquez and Greiling, 2003), historical reconstructions of plant distributions allow environmental scientists to assess and refine climate models (e.g., Whitlock and Bartlein, 1997), and reconstructions of trade patterns and commodity chains show how socioeconomic circumstances produce economic change (e.g., Dicken, 2007). Dramatic changes have occurred over the centuries in the way Earth's surface is understood and mapped. Today, the struggles to find an accurate means of measuring longitude (Sobel, 1995) are of merely historical interest as the GPS has reduced the measurement of location to an almost trivial exercise (except when extreme accuracy is required). Yet the importance of identifying and analyzing patterns has been fundamental to human understanding through the ages—allowing geographical thinkers in Ancient Greece to calculate the circumference of the Earth and those in the modern world to refine understandings of the causes and consequences of urban growth.

The importance of the technological innovations of recent decades lies in their ability to facilitate the collection and analysis of locational information, and to make it possible to produce sophisticated geographical visualizations that can aid scientific understanding and public decision making (Figure 4). These same technologies can be employed to create improved or optimized designs of a wide range of geographically distributed features and facilities, from voting districts to schools, shopping centers, and mass transit routes. Indeed, the geographical sciences have a long history of being employed not only to analyze the world but also to improve it, and there are many strong links with the disciplines of planning, landscape architecture, operations research, and engineering in general. The term *geodesign* has recently emerged as a useful umbrella for the use of geographical data and tools in support of design.[4] Moreover, the geographical sciences hold the key to a vision of planning that is based more on sound evidence than on judgment. Tools such as GIS can be used to subject designs to rigorous analysis based on established and well-tested scientific knowledge, by simulating the effects of known environmental and social processes. For example, options for new transportation infrastructure can be assessed against known patterns of human spatial behavior, and options for new buildings can be assessed against models of heat loss based on sound principles of atmospheric science.

[4]See, e.g., www.geodesignsummit.com (accessed January 28, 2010).

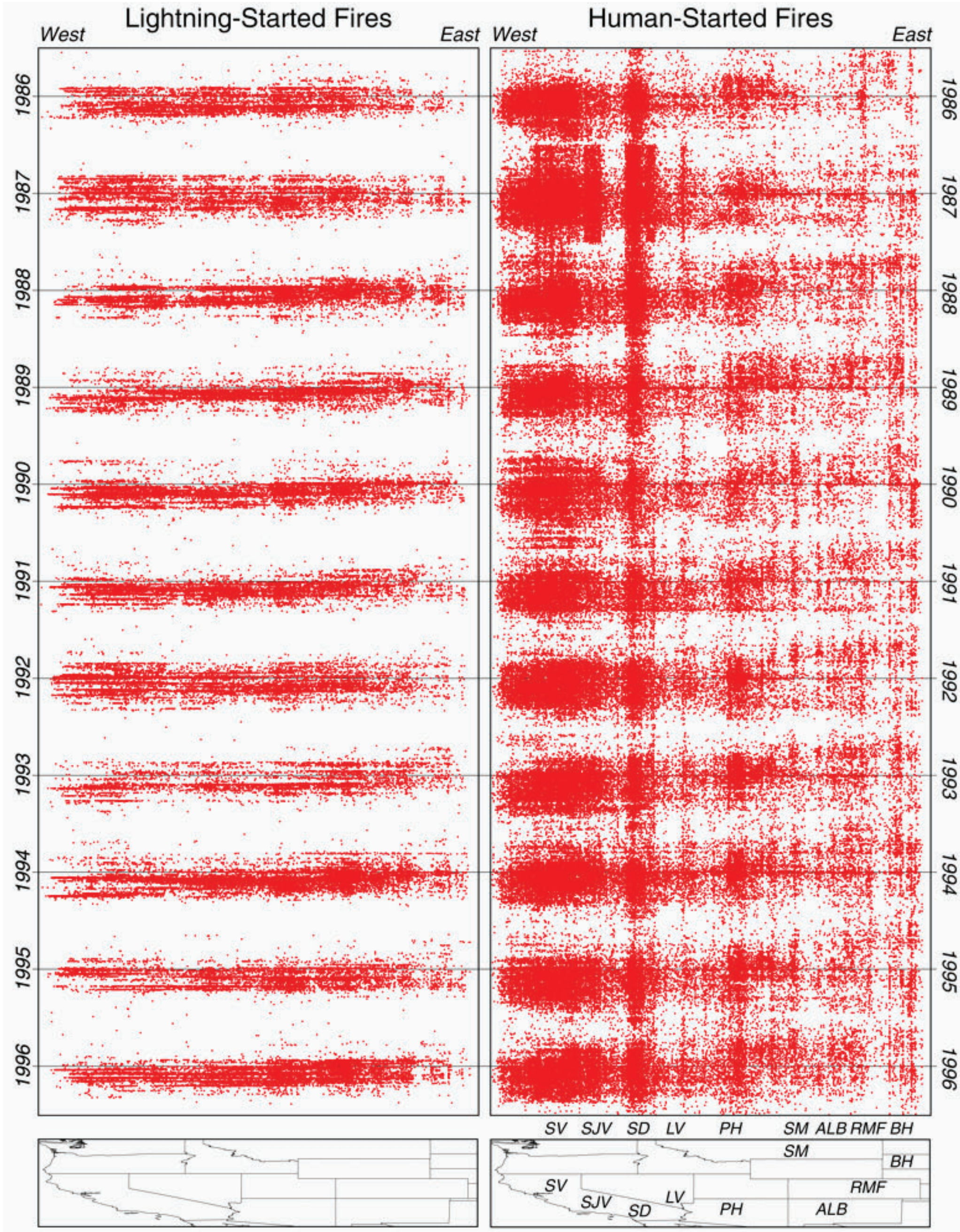


FIGURE 4 Patrick Bartlein and his colleagues' geographical visualization provides insight into where and when different fires occur in the western United States. Building on a visualization technique developed by a Scandinavian climatologist (Hovmöller), their representation shows that lightning-started fires are temporally clustered (the streaks of fire show that widespread outbreaks occur over a few days, and take place earlier in the West than farther east). In contrast, human-set fires show distinct clustering in space that reflects where people live in the West. Because the distribution of fires is spatially uneven, these sorts of insights cannot be gained from conventional fire maps. SOURCE: Bartlein et al. (2008).

Whether enabled by new technologies or not, the collection, analysis, and representation of spatial data are of central importance to the geographical sciences because they promote understanding of how phenomena are related to one another in particular places and across the surface of the Earth.

Investigation of the Relationship Between Large-Scale Processes and Local or Regional Outcomes

A central feature of the geographical sciences is the recognition that circumstances existing at the local or regional scale both affect and reflect larger-scale processes. Much work in the geographical sciences thus proceeds from the idea that there is a great deal to be learned from analyzing "place-based" circumstances and their relationship to larger-scale processes (Massey, 2005). This approach differs from other sciences where research aims to produce generalizations that require averaging across places (thus relegating differences among places to the background). The geographical sciences, by contrast, frequently focus on the circumstances and comparative characteristics of individual places and regions, and then seek to develop broader generalizations by exploring what is general and what is particular about the processes observed in those places (see, e.g., Abler, 2003). Taking such an approach to the Katrina example cited above, for example, involves looking at similarities and differences among places—politically bounded or otherwise—where the processes shaping the impacts of Katrina (state policy decisions, landscape features, upstream land uses, etc.) come together in distinctive ways. Those place-based differences can then be used to assess and refine general models and concepts.

Place-based analysis has long been important in geographical studies (e.g., Cliff and Ord, 1973; Anselin, 1995; Fotheringham et al., 2002), but its significance is increasingly being recognized in other scientific realms, especially ecology, and it has become a core feature of the emerging field of sustainability science (Kates et al., 2001). Place-based approaches have also recently emerged as a key strategic direction of the Obama administration. In an open memorandum dated August 11, 2009, senior White House staff directed the heads of executive departments and agencies to develop effective place-based policies in their preparations for the FY 2011 budget (Orszag et al., 2009). The memorandum includes language that resonates with many of the themes and principles on which the study committee based its work, and which are elaborated in many parts of this report; for example, the memorandum's section defining place-based policy notes that such "policies target the prosperity, equity, sustainability and livability of places—how well or how poorly they function as places and how they change over time."

Landscape Analysis

Investigation of the tangible human and physical features of Earth's surface that exist in particular places is another common feature of geographical investigation. Landscapes are expressions of the processes and events that shape places over time; as such, they offer clues into what has happened and where and why it has happened (Conzen, 2010). Detailed studies of land-use and land-cover change in different regions have shown that population growth and poverty cannot alone explain the changing landscape; economic opportunities and institutional factors need to be considered as well (Lambin et al., 2001). Similarly, studies of continuity and change in urban landscapes have provided insights into the social, cultural, and institutional forces that are shaping the evolution of human communities (Wyly, 1999). Studies of the material landscape are important to the geographical sciences because they offer information and ideas of fundamental importance to the effort to explain the physical and human forces that are shaping Earth's surface over time.

The core concepts and approaches of the geographical sciences have spread across many scientific disciplines and into the everyday practices of business and government; they are now routinely employed by archaeologists, economists, astrophysicists, epidemiologists, biologists, landscape architects, computer scientists, and others (Box 2). They are thus not solely the province of the traditional discipline of geography. Instead, the relationship between geography and the geographical sciences can be understood by using a biological metaphor. The geographical sciences are the result of a successful propagation of the graft of data, technologies, and ways of thinking onto the root stock of geography. The latter continues to be a place where central attention is given to the concepts and tools employed by the geographical sciences, but those concepts and tools have now diffused beyond the formal discipline. The recent decision to change the name of the "Geography and Regional Science"

BOX 2
Spotlight on the Geographical Sciences

In 2008, economist and *New York Times* columnist Paul Krugman received the Nobel Prize in Economics for his analysis of trade patterns and location of economic activity.[a] Krugman won the prize for a mathematical model that helped explain regional disparities. His general equilibrium model focused on the interaction of economies of scale with transportation costs, which provided insights into the spatial consequences of increasing returns. His model formalized and placed within the parameters of the general equilibrium model prior understandings of the economic advantages to be gained from the spatial agglomeration of production and the ways in which such agglomeration contributes to regional disparity, as well as to interregional trade. His work has given rise to what is sometimes termed a "new economic geography" among international trade theorists, who traditionally adopted a neoclassical economics approach to understanding agglomeration (Behrens and Robert-Nicoud, 2009).

[a]See www.nobelprize.org/nobel_prizes/economics/laureates/2008/press.html (accessed December 15, 2009).

program at the U.S. National Science Foundation to the "Geography and Spatial Sciences" program reflects the growing transdisciplinary character of geographical research and analysis. The new program represents an explicit acknowledgment of the cross-disciplinary communities that are now dealing with spatial ideas, data, and techniques.

THE GEOGRAPHICAL SCIENCES AND SOCIETY

The importance of the geographical sciences in the 21st century becomes clear when one considers the extent to which many of the central challenges of our time are tied to changes unfolding in the spatial organization and character of the peoples, places, landscapes, and environments found on the surface of the planet. Earth has always been dynamic—constantly in flux as physical systems and human societies evolve (Turner et al., 1990a). Yet the pace and extent of human-induced changes have reached unprecedented levels in recent decades. Massive numbers of people are on the move; cities are mushrooming in size (Figure 5); ecosystems are being transformed; patterns of economic, social, and political activity are being remade; access to resources and markets are changing; and technological developments are altering patterns of connectivity among peoples and places (Figure 6). With geographical changes so central to the contemporary scene, geographical analysis is necessarily fundamental to contemporary science.

Because of its multidisciplinary character, research in the geographical sciences lends itself to multi-investigator projects, which are becoming increasingly common. The explosive growth in geographical data and technologies can facilitate collaborative projects across vast distances, as researchers tap into shared data banks and make use of virtual systems. The diffusion of information and communication technology has also led to a democratization of science that puts anyone with access to a computer terminal and the Internet in the position of being able to collect and disseminate

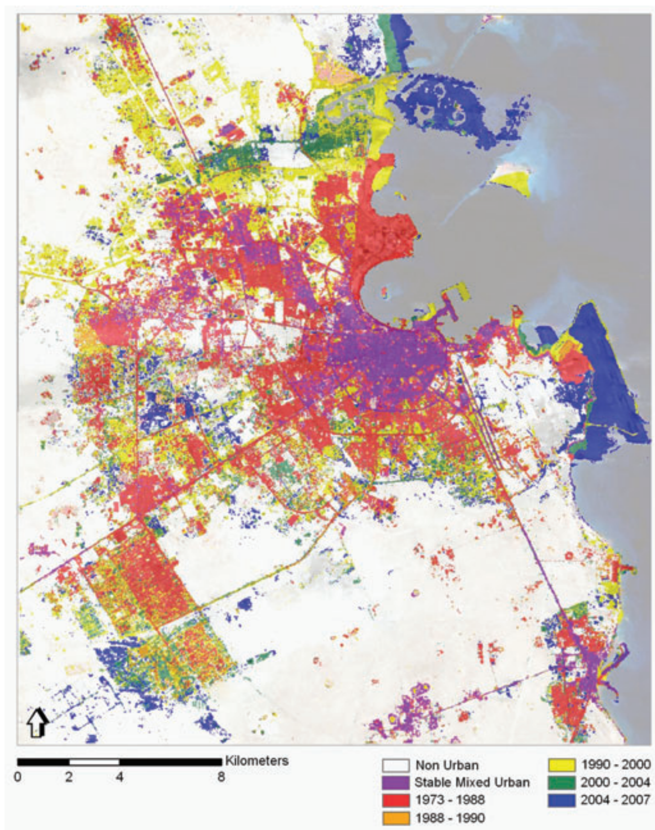


FIGURE 5 This map of urban growth in Doha, Qatar, from 1973 to 2007 illustrates the trend of increasing urbanization occurring in mid-size cities around the world. SOURCE: Karen Seto, used with permission.

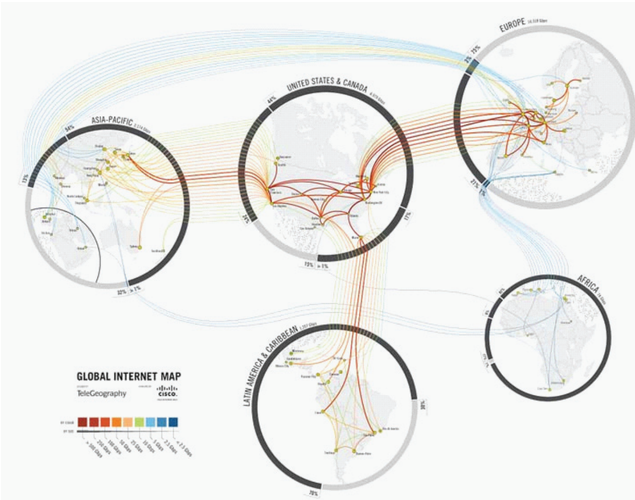


FIGURE 6 This map shows key intercontinental and regional Internet routes and their bandwidth. Disparities in available Internet bandwidth contribute to the differences in access to information and communication technologies that have come to be known as the "digital divide." SOURCE: TeleGeography.

information. Geographical platforms such as Microsoft Virtual Earth and Google Earth are at the forefront of this development. These developments heighten the importance of geographical investigation—both to harness the flood of new geographical information in productive ways and to explore the possibilities and limitations of the information and ideas coming from the rapidly expanding community of "neogeographers" (nonspecialists involved in the collection and assessment of locational data using geographical platforms and technologies). Moreover, when geographical techniques that allow for the precise, systematic monitoring of phenomena are used to collect information on people's activities, complex issues of privacy arise that demand careful consideration by researchers who possess a significant understanding of the nature and power of the geographical technologies involved.

The geographical sciences are also well positioned to strengthen ties between the science and policy-making communities—an increasingly pressing matter as the need grows to respond quickly to the outbreak of disease, manage natural resources in better ways, and improve understanding of complex issues such as inequality and global climate change. Maps and other geographical visualizations are becoming increasingly powerful decision-support tools for the policy sector (Richardson and Solis, 2004). Because geographical visualizations can render complex data in an understandable form, including data about phenomena that change over time (Figures 7 and 8), policy makers are able to see the concrete implications of different choices. Moreover, the concern of the geographical sciences with the relationships among different phenomena, including the physical and human world, put them in a strong position to enrich policy debates by broadening the frame of reference of the matters being considered (Bebbington, 2004;

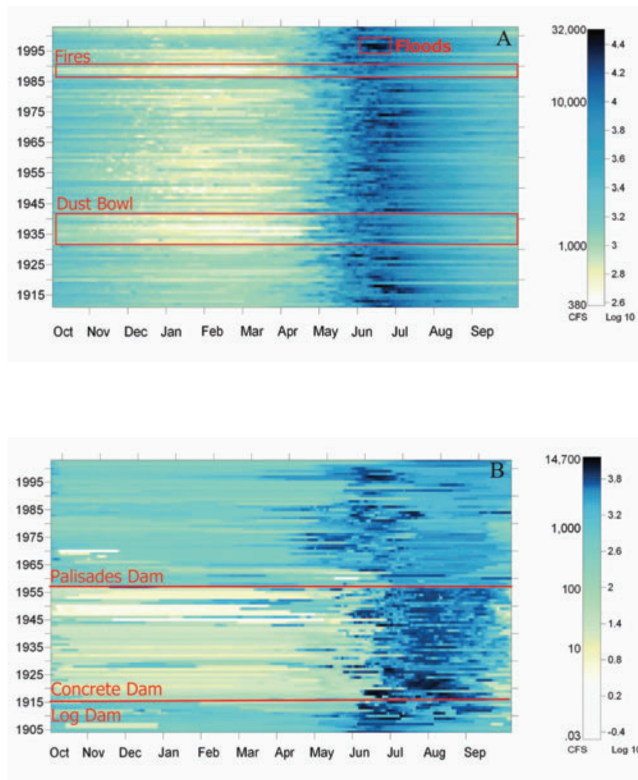


FIGURE 7 Raster hydrographs show average daily discharge (cfs) as a color for each of the 33,969 days of record for Yellowstone River at Corwin Springs, MT (upper) and the 36,529 days of record at the Snake River near Moran, WY (lower). The raster hydrographs enable visualization of daily to seasonal variations within a year by noting changes across each row, and variations between years and decades for a given time of year along the vertical axis. Key events such as the Dust Bowl drought, the low flows prior to and during the Yellowstone fires of 1988, and dam closures are shown. The Yellowstone River has no dams, so flow variations are generally gradual. In contrast, the closure of Jackson Dam on the Snake River led to many abrupt changes in daily discharge. Diagrams such as this make it easier for the general public, managers, and scientists to understand the different timescales over which variations occur.

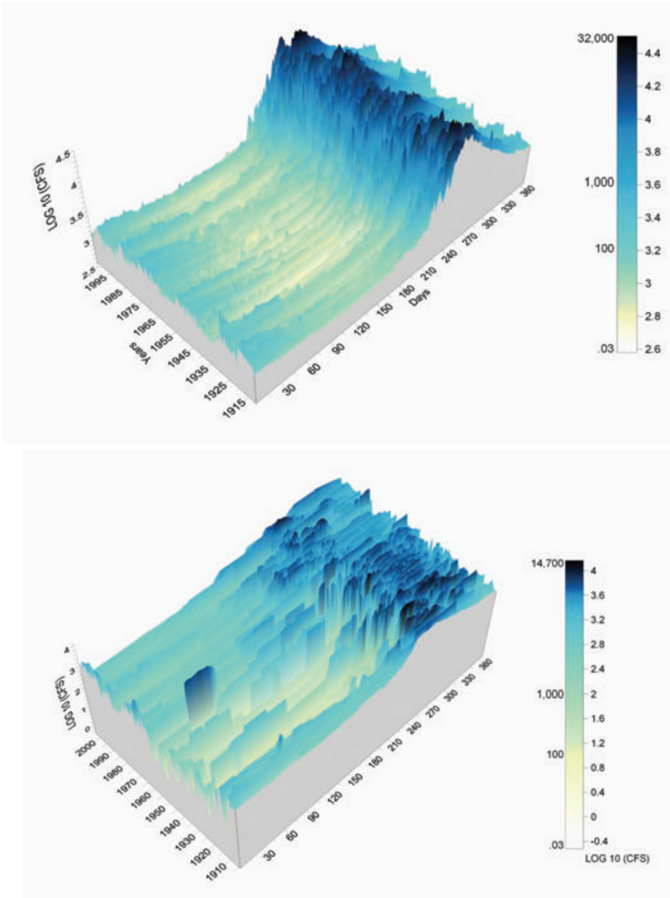


FIGURE 8 Three-dimensional raster hydrographs show the difference in flow regime between a river with no dams (above) and a dammed river where the natural flow regime is significantly modified (lower). Three-dimensional diagrams of this sort make it easier for the general public to visualize and understand how humans affect the river environment. SOURCE: Strandhagen et al. (2006).

Gober, 2004), directing attention to linkages that are of interest to a variety of stakeholders (White et al., 2008), and helping policy makers understand—and factor into their recommendations—the irreducible uncertainties that must be considered when confronting complex, large-scale issues such as climate change (Gober et al., 2009).

COMMITTEE APPROACH

The massive, rapid changes unfolding on Earth's surface provide a logical starting point for considering strategic directions for the geographical sciences, for there is clearly a pressing need to understand what is changing where, why, and at what rate, as well as to assess the implications of those changes for different places and regions. The time is ripe for a consideration of how, and in what ways, the deployment of the concepts, tools, and approaches of the geographical sciences can be particularly strategic in the coming years. With these matters in mind, the National Science Foundation, the U.S. Geological Survey, the National Geographic Society, and the Association of American Geographers requested that the NRC appoint a committee charged with developing a report that would identify strategic directions for the geographical sciences in the coming decade (Box 3).

The committee used the following criteria in selecting questions that would signal strategic directions for the geographical sciences:

- The questions must have clear societal significance.
- The questions must be central to the core concepts of the geographical sciences.
- The questions must relate clearly to the agendas of the larger scientific community.
- The questions must be tractable (i.e., there must be a strong likelihood of achieving significant and demonstrable progress in the next 5-10 years).
- The questions must be answerable using either existing methods and sources of data or methods and data sources that can reasonably be expected to be readily available within the next few years.

Employing these criteria, and drawing on input from the larger community of geographical scientists, the committee developed 11 questions that represent some of the most important opportunities for the geographical sciences to contribute to the task of understanding

BOX 3
Statement of Task

An ad hoc committee will formulate a short list of high-priority research questions in the geographical sciences that are relevant to societal needs. The questions will be written in a clear, compelling way and will be supported by text and figures that summarize research progress to date and outline future challenges.

and responding to the changes that are currently having such a profound impact on the planet (Part II). The committee also spent time discussing what changes in infrastructure, training, and outreach would allow the geographical sciences to make progress toward answering the 11 questions (Part III).

The Process of Identifying Research Questions

The research questions in Part II of this report came out of a committee effort to consider the major scientific and societal questions of the day related to changes unfolding on Earth's surface, and then to identify some of the key ways in which the geographical sciences can contribute to addressing those issues. There is, of course, much debate about what qualifies as a major scientific and societal question, but committee discussions identified four (necessarily overlapping) arenas of inquiry that are widely recognized as being of broad significance: (1) how to understand and respond to environmental change, (2) how to promote sustainability, (3) how to recognize and cope with the rapid spatial reorganization of economy and society, and (4) how to leverage technological change for the betterment of society and the environment. The research questions that lie at the heart of this report were chosen because they raise issues of central importance to these arenas of inquiry that the geographical sciences are particularly well positioned to address.

Understanding and responding to environmental change can be greatly enhanced by bringing a geographical perspective to bear on several key questions:

- How are we changing the physical environment of Earth's surface?
- How can we best preserve biological diversity and protect endangered ecosystems?
- How are climate and other environmental changes affecting the vulnerabilities of coupled human–environment systems?

Promoting sustainability requires addressing questions that probe the geographical dimensions of population change, resource scarcity, and health:

- How and where will 10 billion people live?
- How will we sustainably feed everyone in the coming decade and beyond?
- How does where people live affect their health?

Assessing the impacts of economic and social reorganization can be advanced by raising questions about the changing human geography of the planet:

- How is the movement of people, goods, and ideas transforming the world?
- How is economic globalization affecting inequality?
- How are geopolitical shifts influencing peace and stability?

Making technological change work for the betterment of society and the environment demands consideration of questions about the collection and representation of geographical information:

- How might we better observe, analyze, and visualize a changing world?
- What are the societal implications of citizen mapping and mapping citizens?

In broad terms, the contributions the geographical sciences can make to science and society lie in their potential to improve understanding of the extent and causes of the changes unfolding on Earth's surface, to offer insights into the impacts of those changes, to promote the development of effective adaptation and mitigation strategies in response to those changes, and to facilitate the documentation and representation of Earth's evolving geographical character. The foregoing research questions are strategic because they speak, in overlapping ways, to these contributions. Looking at changes in the physical environment, settlement and mobility patterns, economic and political arrangements, and the collection and representation of spatial data are all critical to understanding the extent and causes of the changes unfolding on Earth's surface. Assessing the impacts of those changes requires looking at the impacts of shifting environmental and resource vulnerabilities and evolving demographic, economic, and social patterns. Developing effective adaptation and mitigation strategies necessitates improved understandings, and better visual representations, of changing environmental and social

patterns and threats to human health and well-being. Finally, assessments of the potential and limitations of new technologies and new ways of collecting data are needed to improve the documentation and representation of geographical change.

The individual research questions do not encompass the full range of issues amenable to geographical investigation, but they represent critically important scientific and societal matters to which the geographical sciences have much to contribute. The order in which they are presented reflects a movement from overarching issues of environmental change and sustainability to matters that bear on particular changes unfolding in the social and technological arenas. This order is not intended to suggest that the earlier questions are more important than the later, however, or that the questions should necessarily be addressed in the order presented. Indeed, there is considerable overlap among and between the questions, and the last question is of relevance to all of the preceding questions.

Part II of this report sets forth each of the research questions, identifies prior work in the geographical sciences of relevance to the question, and outlines particularly promising avenues for advancing understanding of the question. Because the overarching questions are broad, each one is followed by a set of illustrative subquestions that are indicative of more focused research initiatives that could contribute substantially to the effort to address the larger question. The report then turns to Part III, which considers the innovations that will be needed in infrastructure, training, and outreach if significant progress is to be made in addressing the research questions.

Part II

Strategic Research Questions

1

How Are We Changing the Physical Environment of Earth's Surface?

Accelerated human modification of the landscape and human-driven climate changes are fundamentally altering Earth's surface processes and creating ecological challenges that scientists and policy makers are struggling to address. The environmental impacts of human activity are expected to increase as the climate continues to warm and as the world becomes progressively more populated, industrialized, and urbanized. Scientific research has generally succeeded in documenting the magnitude of these biophysical changes, including habitat loss and fragmentation, soil erosion, biodiversity loss, and water depletion and degradation. Yet the exact processes leading to these changes are still not adequately understood and quantified, and we still lack the best methods and techniques for detecting, measuring, and analyzing global change.

Soil erosion provides a prime example to understand what is at stake. Although a natural process, soil erosion has greatly accelerated globally due to cultivation, deforestation, and a host of other land-use practices (Montgomery, 2007a,b; Figure 1.1). Increased soil erosion generates sediment supply that often exceeds the transport capacity of stream systems, leading to vast sediment storage on channel beds, on hillslopes, and in floodplains. This historical sedimentation has already had significant impacts on channel processes, aquatic systems, and fisheries (Waters, 1995; NRC, 2004). Moreover, these legacy sediments represent a future risk because they can be remobilized and introduced into aquatic systems even following landscape amelioration (Walter and Merrits, 2008).

Anticipated climate change will heighten the human impact on the physical environment in many places. Predicting the magnitude and timing of these future impacts remains uncertain, but measurable changes have already occurred climatically (Elsner et al., 2008) and hydrologically over the past few decades, with earlier ice-out dates, reduced magnitudes of spring runoff and summer low flows, and changes in the timing of peak streamflows (Hodgkins et al., 2002, 2003; Huntington et al., 2003, 2004). Future climate change will likely bring greater hydrological and ecological shifts nationally and globally, with potentially profound impacts on water availability (Arnell, 2004; Milly et al., 2005; IPCC, 2007).

Earth surface changes, then, frequently raise resource management challenges, prompting efforts at ecological restoration, and environmental legislation often requires communities or other stakeholders to restore stream channels or wetlands. Yet it is uncertain how, and under what circumstances, most disturbed natural systems can recover, and even less is known about the baseline conditions that may potentially guide restoration efforts. Despite the development of a billion-dollar-a-year restoration industry, the science of watershed restoration is still in its infancy (Wohl et al., 2005; Walter and Merrits, 2008). Large uncertainties remain in other aspects of wetland and river restoration as well, including the ecological and economic tradeoffs of structural ("hard") vs. nonstructural ("soft") approaches and, more importantly, the metrics, goals, and time frames for guiding and achieving watershed restoration. These are just a few examples of the

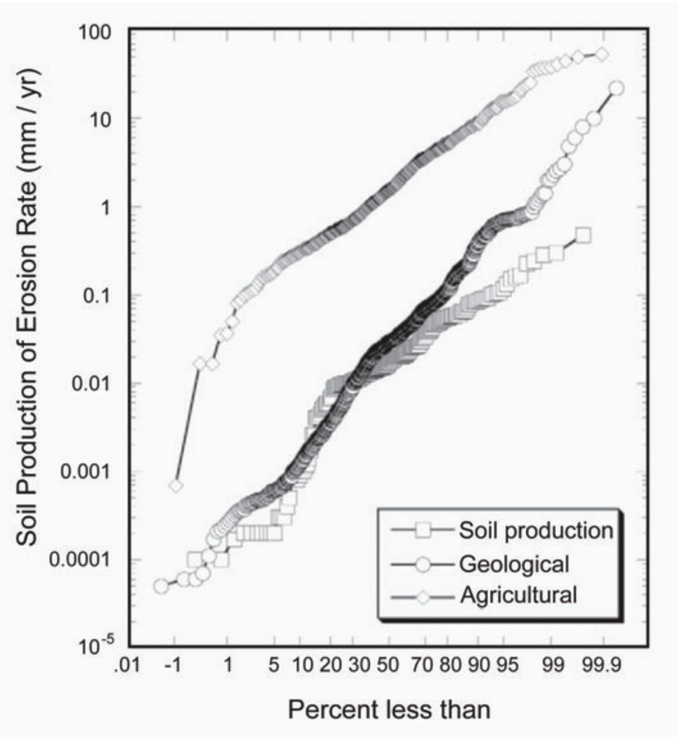


FIGURE 1.1 Comparison of natural erosion rates (over geological time) to agricultural soil erosion rates in relation to rates of soil production. The graph line comprising squares shows the rates of natural soil production, the circles show natural geological erosion, and the top line of diamonds shows agricultural erosion far exceeding the other two rates. SOURCE: Montgomery (2007a).

practical and scientific reasons why we need to better understand the impacts of humans on Earth's physical environment.

ROLE OF THE GEOGRAPHICAL SCIENCES

Because natural processes vary spatially and across scales, a geographical perspective is essential to understanding their nature and character. The perspectives and tools of the geographical sciences used by geographers, geologists, ecologists, and others provide insights into soil erosion, flood magnitude and frequency, and ecological adjustments to climate change on both contemporary and paleotimescales. One significant area of investigation focuses on watershed response to and recovery from environmental changes, including Quaternary (past 2-3 million years) climatic changes and historical human-induced landscape changes. For example, because river systems respond to the integrative effects of climate and watershed processes, changes in streamflow, channel properties, and fluvial deposits provide information on the timing, direction, and magnitude of postglacial climate changes, suggesting that even modest climate shifts can generate significant changes in streamflow (Knox, 1993). Analyses of fluvial stratigraphic records have proved to be important because the identification of paleoflood occurrence extends the researchable time frame of these low-frequency events well beyond the stream gauge record, thus improving flood forecasting (Enzel et al., 1993; Baker, 1998) and capturing the periodicity of highly variable climatic episodes such as El Niño events (Gomez et al., 2004; Magilligan et al., 2008). These paleorecords suggest that climatic stationarity (the mean and variance of a time series) has not remained constant over time (Milly et al., 2008), which raises questions about existing water allocation arrangements because the stationarity assumption is the cornerstone of dam design and water allocation strategies. Higher resolution and longer-term datasets, such as those that can come from dendrochronology, can help capture these statistical shifts.

The geographical sciences have contributed to our understanding of floods as well, especially in relation to land-use changes. The massive construction of dams over the past several hundred years has had a profound impact on the hydrological regime (Figure 1.2), often leading to hydrological modifications exceeding the impacts of climate change (Magilligan et al., 2003; Magilligan and Nislow, 2005). Using archival national data, Graf (1999) identified more than 80,000 dams that have been constructed in the United States—essentially 1 dam per day on average since the signing of the Declaration of Independence. Graf's examination of the geographical location and context of these dams showed marked regional variations in dam number and type; most of the dams in the United States are in the eastern half of the country, although dams with the greatest impact on storage are found in the West (Graf, 1999, 2001). This pattern suggests that, although watershed fragmentation may be considerable in the eastern United States, ecological impacts due to flow reductions may be more significant in the western part of the country. Other field-based studies have provided fundamental insights into the profound

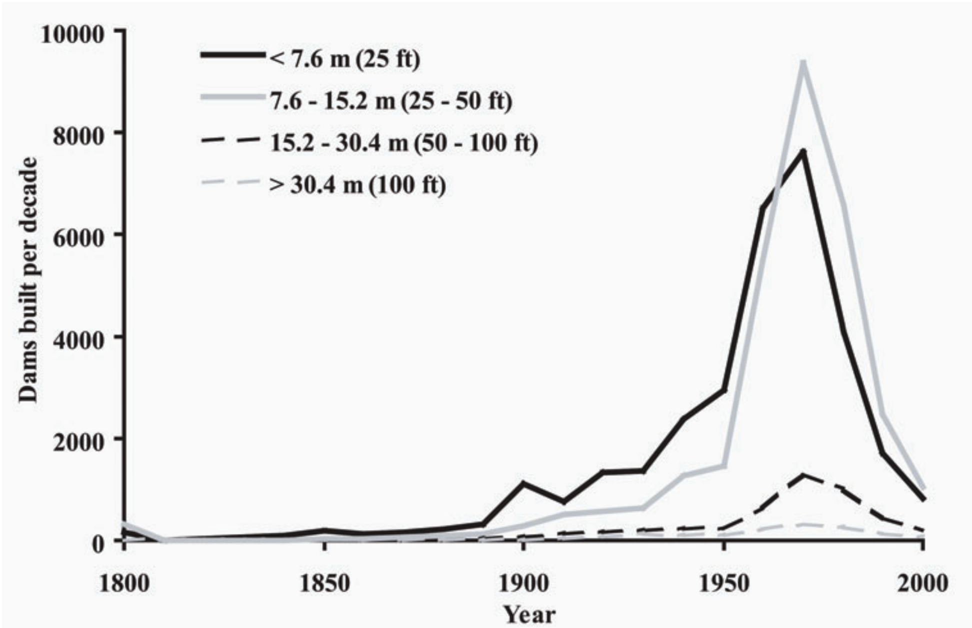


FIGURE 1.2 Number of dams constructed in the United States over the past 200 years (by decade) categorized by dam height. SOURCE: Doyle et al. (2003).

and sustained changes resulting from flow regulation, including changes in channel properties, sediment transport, and reduced ecological habitat (Chin et al. 2002; Phillips et al., 2005).

Because of their concern with spatiotemporal dynamics, geographical scientists have been at the forefront of efforts to use paleoenvironmental data to provide long proxy records of climatic and environmental change. Through techniques such as fossil pollen analysis, fossil charcoal analysis, tree-ring analysis, diatom analysis, chironomid analysis, and various sedimentological and geochemical techniques, geographical scientists have been able to reconstruct changes in terrestrial and aquatic environments on timescales ranging from decades to millennia. Such reconstructions can identify the specific nature of human impacts in the past, provide insight into the natural variability in environmental systems prior to human alteration, and show how environments have responded to past episodes of climate change. They can also be used to validate climate models used for estimating future climate change scenarios (Figure 1.3). In addition to providing qualitative and quantitative information on past environments, paleontological approaches are increasingly being refined and used to provide quantitative records of past temperature, precipitation, drought severity, and river flow (Cook et al., 2007). These records provide the only means of identifying the processes creating climatic variability and determining when anthropogenic climate changes have exceeded natural variability (Diffenbaugh et al., 2006; Herweijer et al., 2006; MacDonald et al., 2008b).

The integrated and synthetic research that is a hallmark of the geographical sciences is essential to address one of the major challenges in climate-change research: determining the natural (as opposed to human) contribution to climatic variability. Many paleoclimatic records and long instrumental data series provide evidence of variations in temperature that persist for decades to centuries. This natural variability in the climate system has two important implications for anticipating the impacts of global warming from increased greenhouse gases. First, if we do not understand their causes and properties, natural variations in climate make it difficult to detect or attribute current and future changes in climate to anthropogenic factors such as increased greenhouse gases. Second, such natural variations are likely to persist even in the face of greenhouse gas–induced climate changes and should be taken into account when planning for climate change. Often the relationships between the ultimate climatic forcing factors are mediated by complex relationships between the atmosphere, oceans, and land surface that play out differently from place to place (Feddema et al., 2005).

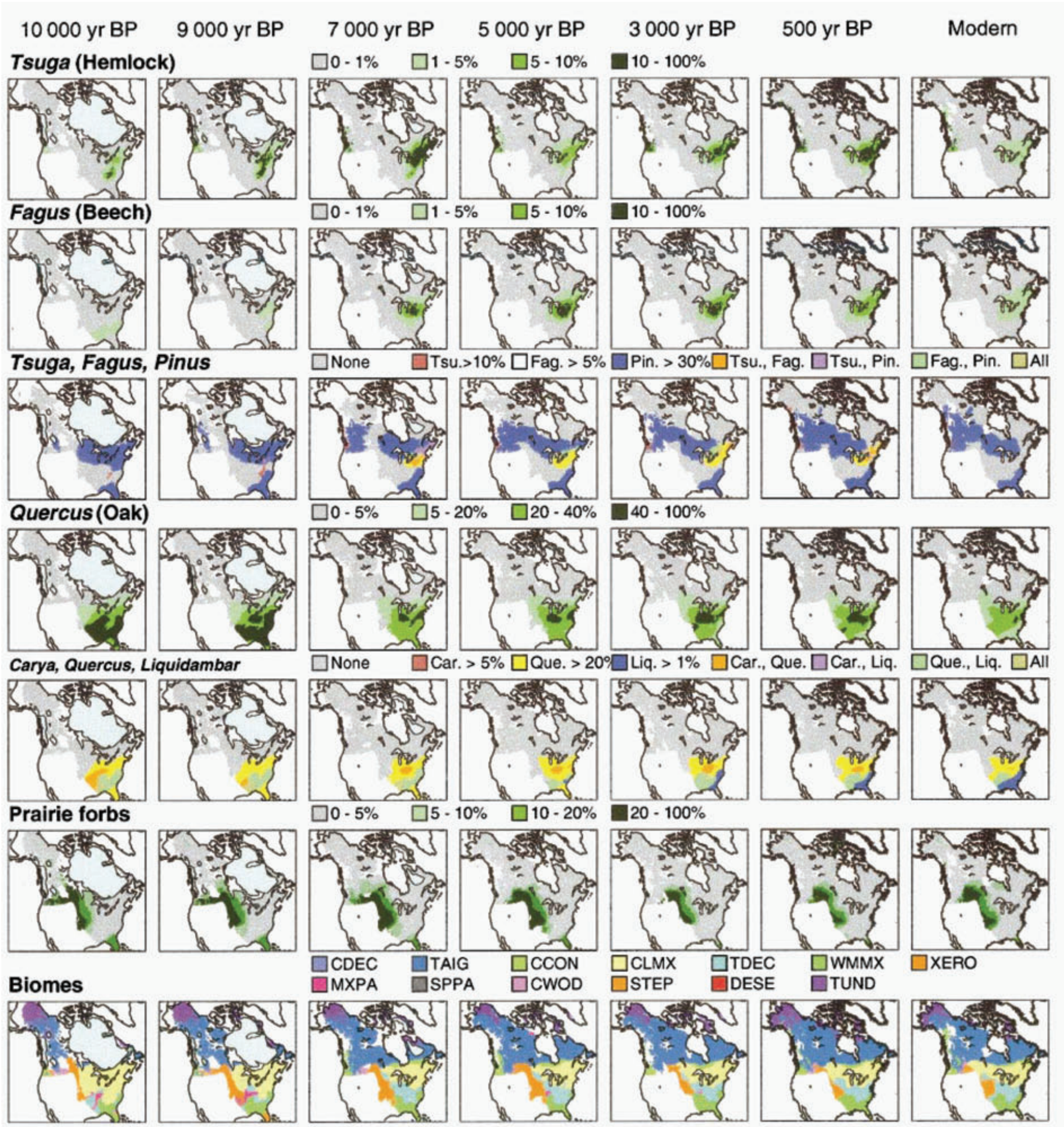


FIGURE 1.3 A mapped summary of changes in plant taxa distributions and biome distributions over the past 10,000 years based on sites in the North American Pollen Data Base. NOTES: CCON = cool conifer forest, CDEC = cold deciduous forest, CLMX = cool mixed forest, CWOD = conifer woodland, DESE = desert, MXPA = mixed parkland, SPPA = spruce parkland, STEP = steppe, TAIG = taiga, TDEC = temperate deciduous forest, TUND = tundra, WMMX = warm mixed forest, XERO = xerophytic scrub. SOURCE: Williams et al. (2004).

The synthesis of different measures of climate change over long temporal scales and across space is required to link particular forcing factors to climatic variations. The following questions are examples of research that would be particularly productive to pursue as part of the effort to refine understanding of the impacts of humans on the biophysical environment. Examples from the fluvial sciences are used to illustrate the importance of the research, largely because watershed processes are major landscape-forming agents. However, applications in the coastal, aeolian, hillslope, weathering, and glacial sciences also represent important avenues for research.

RESEARCH SUBQUESTIONS

What are the natural rates of Earth's surface processes and how has human activity affected them?

Human activity has altered terrestrial, aquatic, and marine ecosystems, and these effects exceed natural baseline conditions. Although progress has been made in determining natural rates of earth-surface processes relative to anthropogenic effects, more research is needed across a suite of processes and regions, with greater attention paid to theoretically informed, empirically grounded assessments of the causes and consequences of anthropogenic disturbance. Anthropogenic impacts have been profound across a suite of earth-surface processes. The significance and scope of these impacts is evident in fluvial systems, for example. Yet erosion and transport rates of sediments stored within watersheds are still poorly understood, as is the residence time of these sediments. Moreover, sediments stored in floodplains represent a vast but currently unknown reservoir of material. These sediments are often contaminated with agricultural pesticides and herbicides. If stored for an adequate time, the toxicity of these contaminants attenuates, but if released by subsequent channel erosion, they may lead to progressive degradation of biotic habitats and contribute to degraded water quality, especially if resulting sediment concentrations exceed Environmental Protection Agency water quality standards for turbidity.

The renewed focus on landscape evolution requires accurate measures of erosion and sediment yield and necessitates studies to determine what component of the total contemporary sediment yield can be attributed to the human imprint. The application of contemporary measured sediment yields to these long-term studies may lead to unknown errors in calculating long-term (geological time) landscape erosion rates. On more contemporary timescales, the recent application of fallout radionuclides, such as ^{7}Be, ^{137}Cs, and ^{210}Pb, has led to greater understanding of erosion and sedimentation rates and their spatial variability (Walling et al., 1999; Kaste et al., 2006), but more studies are needed over larger spatial scales to more accurately link processes of erosion to sedimentation and contaminant sequestration.

Equally important, more refined geographical analysis of hydrological responses to climate and environmental change can provide insight into the variable contributions of nature and humans to earth-surface changes. Climate models generally agree that wet areas will become progressively wetter (IPCC, 2007), but it remains uncertain how that atmospheric shift will translate hydrologically. Fluvial theory suggests that the magnitude and frequency of floods will increase as the climate gets wetter, but the impacts may be more complex, including changes in the timing of floods and the relative shift in the relationship between sediment peaks and streamflow. Previous research on paleofloods provides important insights into fluvial responses to climate change. Research in this vein is spatially incomplete, however, with most of the work restricted to the United States and Western Europe (Baker, 2008). More studies are needed globally, and past flood chronologies need greater temporal calibration and resolution. Recent advances in dating techniques, including optically stimulated luminescence (OSL), can help in this task, because they allow for more accurate dating of paleofloods, especially in regions where ^{14}C dating is limited, such as in deserts or in situations exceeding the temporal bounds of ^{14}C dating (~50 ka).

How can we best plan for and implement landscape restorations when disturbed areas are constantly influenced by human activity?

Few places on Earth remain unaffected by human activity. As anthropogenic disturbances have increased in magnitude and areal coverage during the past century, there has been a corresponding increase in efforts to mitigate their impacts. Hydrological systems, for example, have been especially affected by human activity, ultimately leading to demands for remediation; however, the science of watershed restoration lags far behind the need for, and application of, mitigation strategies (Wohl et al., 2005). Management strategies range from complete preservation and removal of direct human impacts to attempts to restore and rehabilitate some element of biophysical functioning and ecological integrity. Potential approaches may be constrained by legal and socioeconomic limitations, but also by not having an accurate understanding of biophysical processes, relaxation times, and the scientific metrics of successful restoration.

Because of extensive channelization, damming, and other structural modifications, most rivers—both in the United States and globally—are ecologically impaired, resulting in a wide range of impacts including habitat loss and fragmentation, interruptions in the hydrological regime, and changes in water quality and temperature (Stanford and Ward, 1993, 2001; Poff et al., 1997; Magilligan et al., 2003). To combat this degradation, efforts are under way to restore everything from small tributaries to rivers as large as the Rhine and ecosystems as vast as the Everglades. Management agencies such as the U.S. Forest Service and the Nature Conservancy are demanding the implementation of "environmental flows" that capture predisturbance conditions, but these goals may not be attainable given existing stakeholder demands and sociopolitical realities. Moreover, unknown complexities exist where, for example, establishing a flow regime to meet hydrological connectivity may have repercussions on sedimentation and aquatic habitat (Kondolf and Wilcock, 1996). More research needs to be directed at determining the correct magnitude and timing of flows to accommodate management goals within a context of humanized landscapes where complete restoration is impractical and where it is difficult or impossible to assess the precise character of a system not disturbed by humans. There needs to be better development of process-based restoration efforts (Kondolf et al., 2006; Doyle et al., 2007; Simon et al., 2007). In some instances, though, river restoration cannot be fully achieved because of social and technical limitations; hence there is a growing focus on river rehabilitation aimed at reestablishing fundamental riverine processes (Wohl et al., 2005). Successful restoration and rehabilitation efforts typically require collaborative research teams of geographers, ecologists, and other scientists conducting long-term field experiments and manipulations to assess the best possible restoration outcomes.

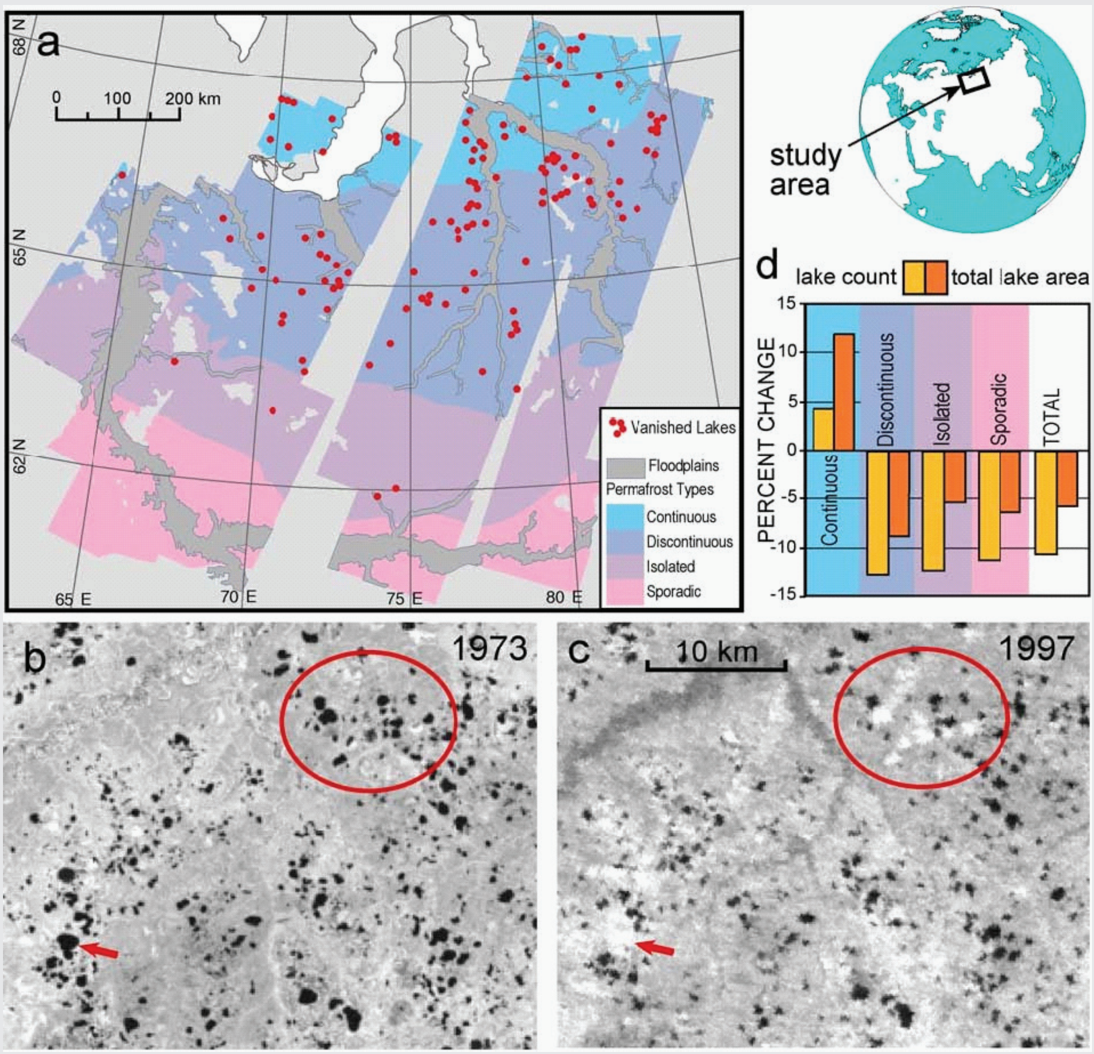
The coming decades will require greater attention to sediment impacts associated with changing environmental conditions. For example, with more than 500 dams removed thus far in the United States and many more targeted for removal in the relatively near future, there is a pressing need to advance understanding of the impacts of sediment fluxes as stream channels reestablish new equilibrium profiles. Moreover, the release of stored sediment has unknown ecological impacts. As dam removal is increasingly recommended as a panacea for habitat restoration, it is important to consider whether the release of stored sediment, in some instances, may be harmful to ecosystem functioning (Stanley and Doyle, 2002; Sethi et al., 2004; Snyder et al., 2004). The focus on sediment dynamics will require more sophisticated approaches, including numerical modeling, parameter estimation, flume studies, and field-based empirical approaches. Novel tracing studies are emerging to document sediment fluxes and residence times, including single-grain OSL, geochemical tracers such as ^{7}Be and ^{210}Pb, and active (radio) and passive (iron, magnetic) tracers (Schmidt and Ergenzinger, 1992; DeLong and Arnold, 2007; Salant et al., 2007). These approaches need refinement and broader application across a continuum of depositional environments. And studies that focus on the role of geographical context in producing detected stream-channel adjustments offer tremendous potential across the geosciences.

What tools offer particular promise in the effort to detect and measure changes in earth-surface processes, and how might those tools be deployed to enhance understanding of the impacts of humans on Earth's physical environment?

Advances in remote sensing and geographic information systems have radically transformed the physical sciences, providing innovative opportunities to measure, analyze, and visualize geographical data and to raise and answer important new research questions (see Chapter 10). The magnitude and scale of environmental change makes it imperative that we utilize these new technologies to document global change, and to develop appropriate mitigation and adaptation strategies. Remote sensing technologies have enormous potential to facilitate the identification of regions at risk and to assess the magnitude and types of environmental changes that are occurring. They are also critical to the development of early warning systems. Moreover, some of the most far-reaching future environmental changes are likely to occur in regions lacking adequate data or long-term databases (e.g., eastern Africa, southwestern Asia, and the polar regions) (IPCC, 2007)—making the application of remote sensing in these areas all the more important (Box 1.1). Remote sensing analysis has

BOX 1.1
Monitoring Changing Hydrological Conditions in Polar Regions Using Remote Sensing

With global climate change models indicating that high-latitude regions will experience the greatest impact of global warming, there has been a concentrated effort to understand the complex environmental shifts occurring in polar regions. Because these regions are vast and often lack on-the-ground observation and data collection, remote sensing offers an important opportunity to monitor and track hydrological, ecological, and geomorphic adjustments. Using a historical archive of satellite images in Siberia, Smith et al. (2005) monitored the changing surface area of more than 10,000 large lakes and showed a widespread decline in lake abundance and area since 1973 (see Figure). The rapid warming occurring in this vast region over the ~50 years generates major permafrost thawing, leading to significant subsurface lake drainage. The total number of large lakes (those >40 ha) decreased by ~11 percent between 1973 and 1997-1998. In general, most lakes shrank to sizes below 40 ha rather than disappearing completely, with total regional lake surface area decreasing by ~6 percent. Satellite imagery revealed that 125 lakes vanished completely. Their subsequent monitoring further confirms that none of these lakes have refilled since 1997-1998 and are thus considered to be permanently drained.



(A) Locations of Siberian lake inventories, permafrost distribution, and vanished lakes. (B) Total lake abundance and inundation area have declined since 1973, including (C) permanent drainage and revegetation of former lakebeds (the arrow and oval show representative areas). (D) Net increases in lake abundance and area have occurred in continuous permafrost, suggesting an initial but transitory increase in surface ponding. SOURCE: Smith et al. (2005).

already proved beneficial in documenting the recent shrinking of subtropical highland glaciers (Coudrain et al., 2005), but more detailed, longer-term remote sensing can expand our understanding further. Similarly, remote sensing is capturing the widespread fragmentation of tropical forests (Morton et al., 2006), yet longer term geographical records are needed, as are remote sensing studies and on-the-ground surveys that can synthesize and analyze the integrated physical and biological effects of deforestation on human and biological communities.

One of the most significant recent advances in remote sensing is lidar (light detection and ranging), which provides very high resolution topographic data (Figure 1.4). Lidar systems transmit pulses of visible or near-infrared laser light from an aircraft to the surface. By measuring the time it takes for the pulses to be reflected, the elevation of the surface can be calculated. Because the costs are relatively high, most lidar missions cover only relatively small areas, and many regions have not yet been mapped. Nonetheless, the centimeter-scale resolution of lidar offers enormous opportunities in the physical sciences, especially in documenting global sea-level change, erosion and uplift of mountain ranges, agricultural soil erosion, glacial retreat, and postflood stream-channel changes. When multiple lidar returns are recorded for each location, the data can be used both to map the topography of the ground surface and to infer characteristics of vegetation, such as tree height (Andersen et al., 2006).

Other remote sensing sources of topographic information also exist. Interferometric radar has been used to map broader areas at coarser spatial resolution than lidar systems, as demonstrated in the February 2000 Shuttle Radar Topography Mission, which mapped 80 percent of the world's land surface during an 11-day

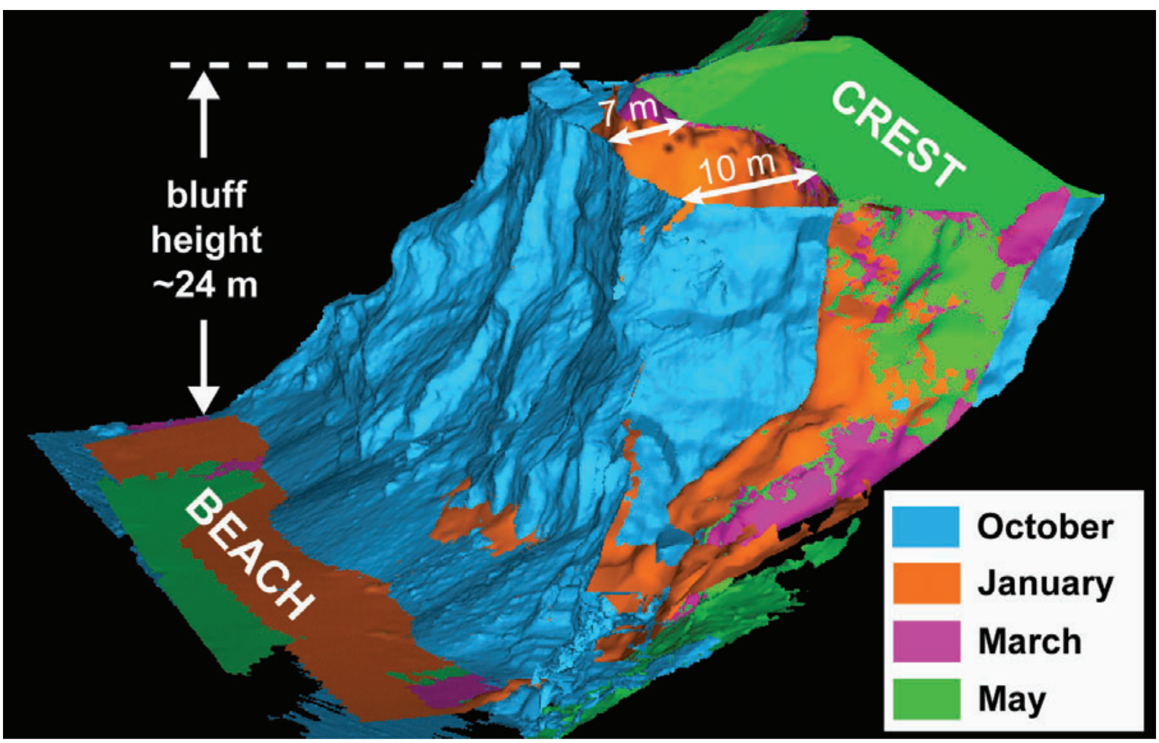


FIGURE 1.4 A high-resolution lidar image of a coastal bluff south of San Francisco, California, showing erosion over a 6-month period. The majority of bluff loss occurred in the fall (blue), with smaller sections of the bluff eroding in the spring (orange and pink) for a total horizontal loss at the top of the bluff of 7-10 meters (23-33 feet). Lidar also allowed the total volume of the eroded bluff material to be calculated, a key component in the development of an accurate sediment budget for this section of coastline. Such lidar-derived information is valuable to coastal managers interested both in the timing and magnitude of coastal erosion events and understanding where material lost from eroding bluffs is likely to accumulate. This information can guide development decisions adjacent to the bluffs, but was not commonly available prior to the development of lidar. SOURCE: Brian Collins, U.S. Geological Survey, 2004.

period. When interferometric radar data are collected at multiple points in time, differential interferometric analysis can be used to measure centimeter-scale changes in topography over broad areas, such as those resulting from seismic activity along faults, ground subsidence due to groundwater or oil extraction, and changes in glaciers and ice sheets (Kwok and Fahnestock, 1996; Bürgmann et al., 2000). Although interferometric radar provides coarser resolution than lidar systems, its global coverage from satellite platforms is currently more temporally and spatially extensive, and it shows exceptional promise for many applications in the physical sciences.

There are several areas in watershed science that could benefit from remote sensing applications. The U.S. Geological Survey operates a dense network of stream gauges in the United States, yet there is a paucity of gauges globally and thus large parts of the world lack adequate data on streamflow. With the application of SAR (synthetic aperture radar) and MODIS (Moderate Resolution Imaging Spectroradiometer)—two satellites gathering remote sensing data—it is becoming increasingly possible to measure streamflow (Smith, 1997; Brakenridge et al., 1998, 2007) and sediment load (Gomez et al., 1995) from satellites. Other promising approaches include mapping of stream-channel habitat using hyperspectral imagery (Marcus et al., 2003; Marcus and Fonstad, 2008) and integrating meteorological data and watershed response (Smith et al., 2007). Although launched for mapping gravity anomalies and crustal characteristics, one of the important extensions from the GRACE (Gravity Recovery and Climate Experiment) satellite has been the documentation of groundwater levels from space (Strassberg, et al. 2009). Destined to be launched in 2013 (NRC, 2007a), the SWOT (Surface Water Ocean Topography) satellite mission offers enormous potential to monitor global-scale hydrological changes and map surface-water elevations. These rapid and remote techniques have great potential for the geographical study of fluvial systems. The utilization and incorporation of remote sensing into a range of investigations of hydrological and ecological phenomena offer researchers opportunities for collaborative and interdisciplinary studies (Walsh et al., 2003) that can lead to more spatially explicit, and therefore more useful, models of biophysical processes.

SUMMARY

As the foregoing examples make clear, spatial analysis, field-based research, geographical visualization, and fine-grained contextual studies are critical to assessing the magnitude and types of global biophysical adjustments that are presently occurring. The approaches and techniques of the geographical sciences can help identify and quantify the biophysical changes unfolding on Earth's surface, and they can offer insights into the processes shaping those changes at different scales. Geographical science approaches and techniques thus have an important role to play in advancing scientific understanding of biophysical changes and facilitating the efforts of resource managers and policy makers to confront Earth's changing environment.

2

How Can We Best Preserve Biological Diversity and Protect Endangered Ecosystems?

The extinction of plant and animal species is not only decreasing Earth's biodiversity and depriving humans of potential resources for food, medicine, and simple enjoyment of nature; it is endangering the functioning of ecosystems and potentially precipitating a cascading effect of increased ecosystem loss and further erosion of biodiversity (Kinzig et al., 2001; Loreau et al., 2001, 2002). Ecosystems are critical to human welfare. They sequester carbon, produce oxygen, generate chemical energy from sunlight, and are integral to soil formation, nutrient cycling, food production, wood and fiber production, the regulation of water flow, and the transference of water to the atmosphere. Ecosystems have always been in flux, but as the Millennium Ecosystem Assessment (MEA) makes clear:

> Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth. (MEA, 2005:1)

Human activity is the likely cause of the extinction or disappearance of close to 850 species over the past 500 years (Baillie et al., 2004). The rates of plant and animal extinction today are conservatively estimated to be 100 times to more than 1,000 times greater than past average extinction rates calculated from fossil lineages (MEA, 2005). The causes of past and present extinctions include a number of human-driven factors such as habitat and ecosystem destruction and fragmentation, overexploitation of species through hunting and fishing, competition and predation by invasive species, and pollution (MacDonald, 2002; MEA, 2005; Loreau et al., 2006; Worm et al., 2006). At the global scale, the biosphere can be grouped into geographical regions called biomes in which climatic conditions and vegetation structure are internally similar, but differentiable from other biomes. The majority of some biomes, such as the temperate forests or Mediterranean woodlands and shrublands, have already been converted to cultural landscapes (Figure 2.1).

Today, tropical forest systems and wetlands are being hit particularly hard by habitat destruction and fragmentation (e.g., DeFries et al., 2005). On top of this, rates of extinction could increase catastrophically as species find themselves unable to adjust geographical ranges quickly enough in response to climate change. In an analysis of the impacts of a moderate climate warming scenario on more than 1,000 plant and animal species in Mexico, Australia, South America, and Africa, Thomas et al. (2004) concluded that between 15 percent and 37 percent of these species would be committed to extinction by 2050. Malcolm et al. (2006) estimated that up to 43 percent of species in some biodiversity hotspots may face extinction owing to changing climate and vegetation distributions caused by global warming.[1]

[1]Widespread concerns about the rate and impact of biodiversity and ecosystem loss has generated important international programs of research such as the DIVERSITAS initiative supported by governments in Asia, the Americas, and Europe.

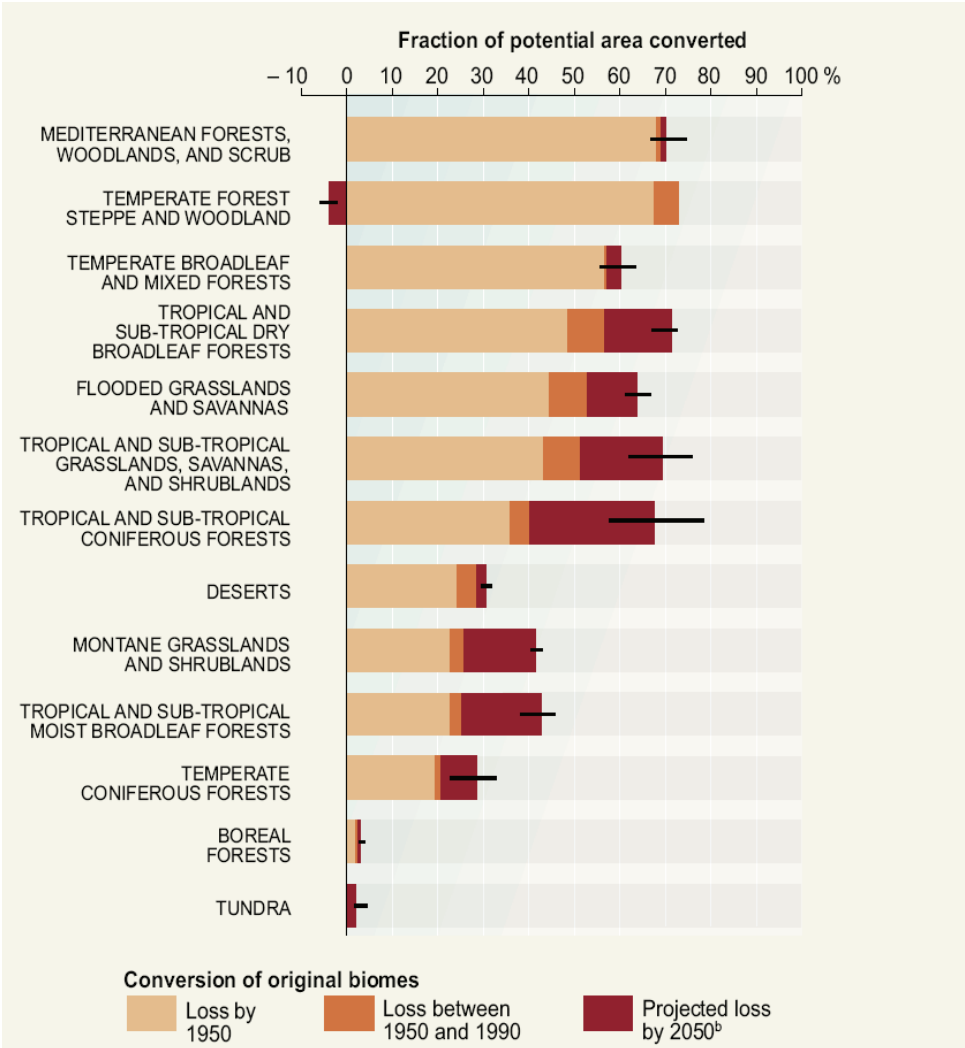


FIGURE 2.1 Past and projected conversions of major biomes to cultural landscapes and loss of original ecosystems. SOURCE: MEA (2005).

ROLE OF THE GEOGRAPHICAL SCIENCES

The geographical distribution of biodiversity, threats of biodiversity and ecosystem loss, and regions where conservation efforts should focus are not evenly distributed, but display distinct spatial patterning at all scales, from local to global (Brooks et al., 2006; Kremen et al., 2008). Species richness decreases from the equator poleward (Figure 2.2). Within this general pattern, certain geographical areas have notably high numbers of species, many found nowhere else in the world. These areas of high endemic species richness are referred to as biodiversity hotspots and are often regions prone to significant ongoing ecosystem alteration and loss (Figure 2.2). The role that location and geographical context play on biodiversity and ecosystem loss makes the geographical sciences integral to understanding this issue.

Through field studies, remote sensing, and ecological modeling, the geographical sciences document and explain biodiversity distribution and contribute to its preservation through strategies aimed at optimizing conservation (Church et al., 2003). Scientists are still seeking to determine how many species of plants and animals the planet supports. The lack of information is particularly notable in marine and freshwater systems, which have received less attention than their terrestrial counterparts (Richardson and Poloczanska, 2008).

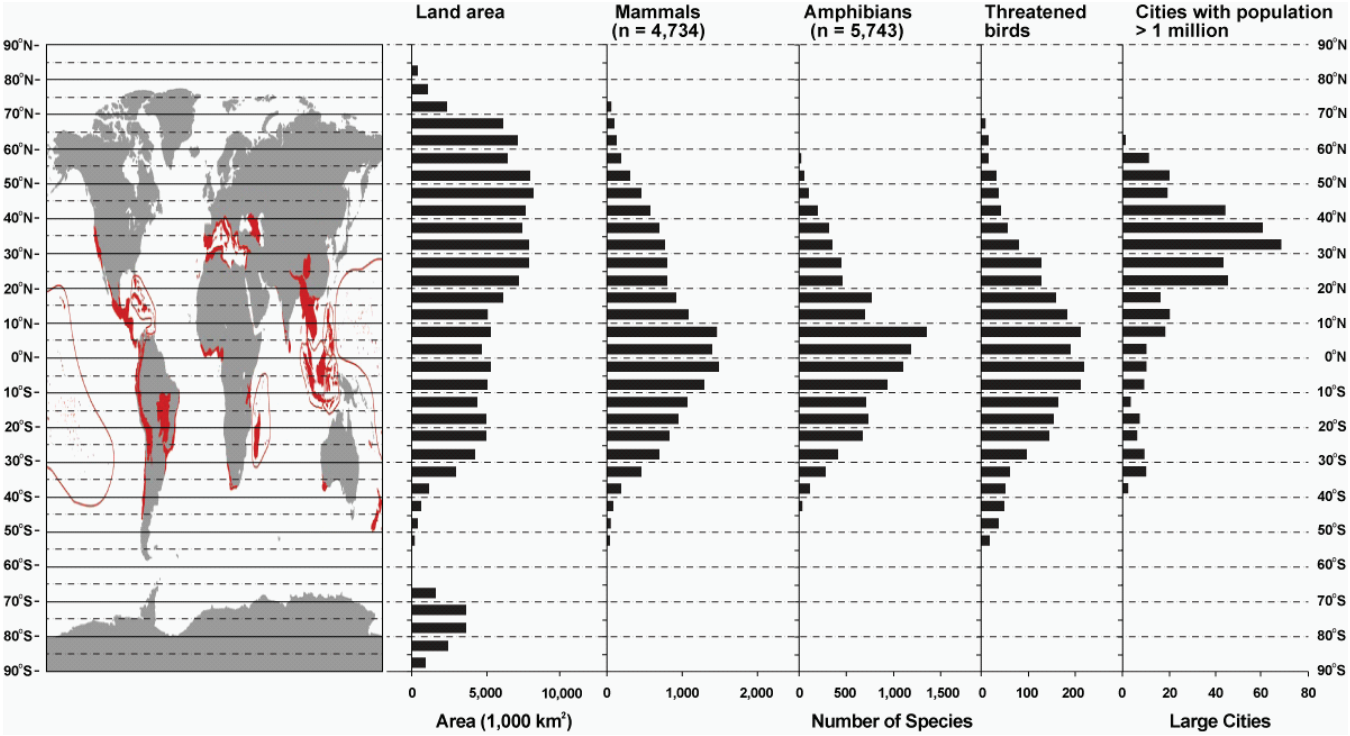


FIGURE 2.2 Map of Earth with the locations of major biodiversity hotspots in red (Myers et al., 2000), the latitudinal biodiversity gradients for mammals, amphibians, and threatened bird species (MEA, 2005), and cities with populations greater than 1 million (UN, 2009). SOURCE: Adapted from Myers et al. (2000); MEA (2005); and UN (2009). Used with permission of Island Press, Washington, D.C.

Geographical scientists have demonstrated that both biophysical and sociocultural dimensions are central to the causes and consequences of land-cover and land-use change, and they have advanced understanding of how human circumstances (e.g., social marginalization) and associated processes (e.g., policy changes) affect biodiversity or ecosystem loss. This has resulted in the development of the emerging interdisciplinary field of land change science (LCS), the goal of which is to develop integrated explanations of land change (Turner et al., 2007). The Global Land Project of the International Geosphere-Biosphere Programme represents an international effort to understand the interacting drivers, patterns, and impacts of such changes.

An exposition of the aims of LCS and insights into the role of the geographical sciences is provided by a recent special feature on the topic in *Proceedings of the National Academy of Sciences* (Turner et al., 2007). In one study particularly representative of the spatial and integrative nature of the geographical sciences, Irwin and Bockstael (2007) use geographical pattern metrics of land-use change in Maryland from 1973 to 2000 to document the spread of urban development and the resulting fragmentation of habitat (Figure 2.3). They drew three conclusions. First, contrary to earlier work on national patterns, urban growth is an ongoing phenomenon and is being underestimated in other studies because of insufficient attention to increasing low-density exurban development. Second, the increasing growth is often peripheral and low density and is leading to increased habitat fragmentation and loss. Third, the environmentally sensitive Chesapeake Bay region is actually experiencing increased development because of its commercial and recreational amenity value. The movement of people to economically and environmentally attractive urban areas causes habitat loss and fragmentation, but much remains to be done to assess the precise impacts of these demographic shifts on ecosystems and biodiversity. It follows that an important question for the geographical sciences, environmental sciences, sociology, economics, and environmental ethics is how to manage the growing

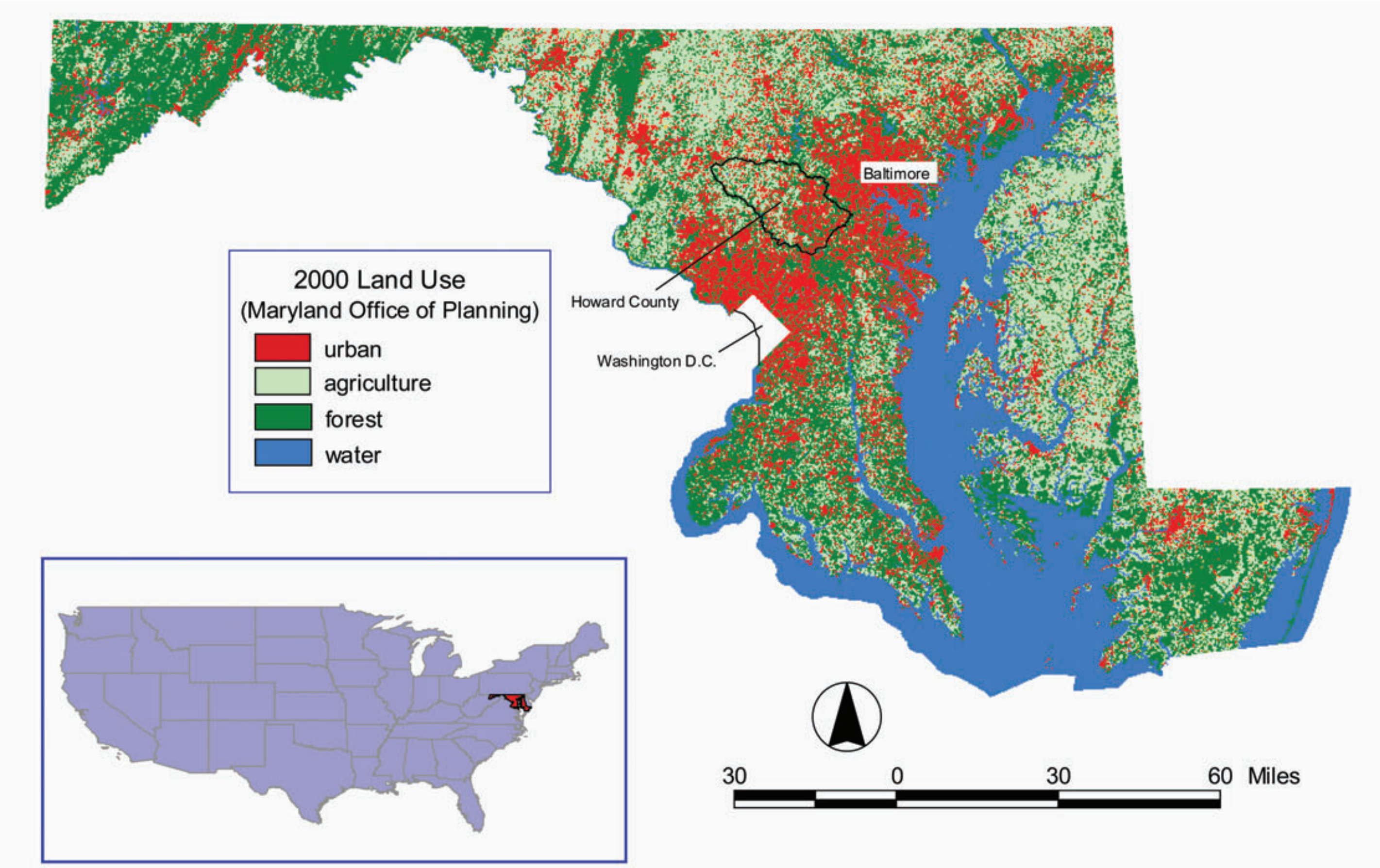


FIGURE 2.3 Land use in Maryland in 2000. Note the fragmentation of forested and agricultural land on the outskirts of the Baltimore-Washington metropolitan area, which Irwin and Bockstael show from longitudinal data has been ongoing since the 1970s. Also, the increasing concentration of urban development along the shores of the Chesapeake Bay reflects an influx of development because of the commercial and recreational amenities of the ecologically sensitive waterway. Urban growth is in this case affecting both terrestrial and estuarine ecosystems. SOURCE: Irwin and Bockstael (2007).

pressures for urban development in a manner that balances demands and biodiversity/ecosystem protection (see also Chapter 4). Understanding the geographical patterns and rates of such changes in land use through use of the geographical sciences can help elucidate the trade-offs involved.

RESEARCH SUBQUESTIONS

How is biodiversity distributed and controlled?

The number of species that comprise the biodiversity of the planet is unknown, with estimates ranging between 5 million and 30 million. Of this number, only about 2 million have been scientifically described (Groombridge and Jenkins, 2002; MEA, 2005). The spatial distributions of many of the known species remain poorly articulated. The geographical sciences can help address this lacuna through the integration of biological censuses with measurements of physical environmental variables. Field-based measurements can be obtained through traditional ecological census methods and physical geography approaches, but it is impossible to cover the expanse of the biosphere, particularly in remote and difficult-to-access tropical regions. Hence, estimating species distributions and biodiversity requires integrating the results of field research with remote sensing data, and using geographic information systems (GIS) to overlay and extrapolate biological and environmental variables (e.g., Cohen and Goward, 2004; Gillespie et al., 2004, 2008; Goetz et al., 2007; Figure 2.4).

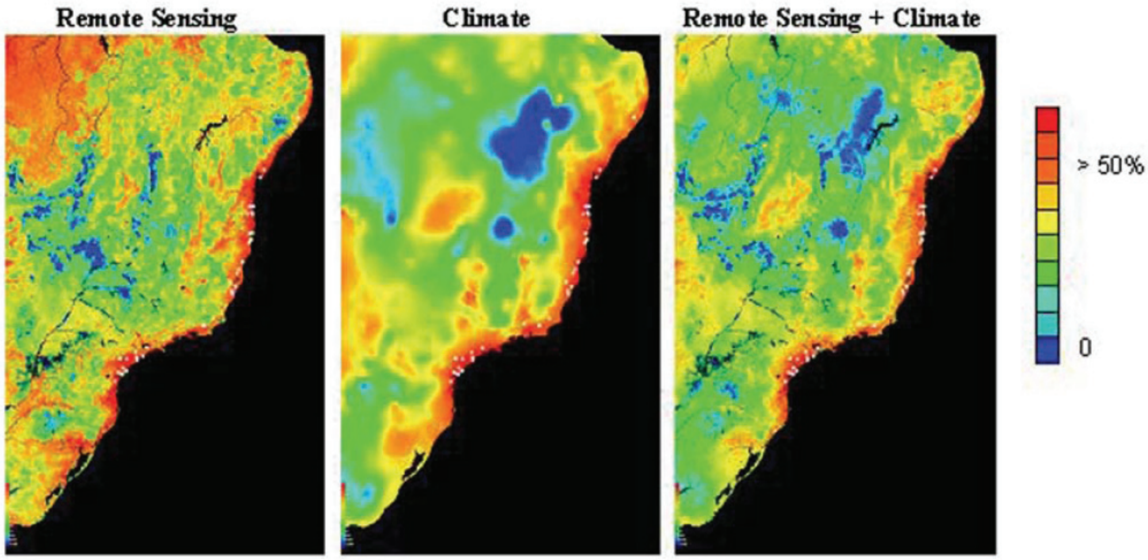


FIGURE 2.4 Results of a maximum entropy model provide an example of how remote sensing data on landscape/vegetation and climatic data can be combined to improve understanding of fine-scale features that influence the spatial distribution of species, in this case *Carpornis melanocephala* (black-headed berryeater) in Brazil. Higher values indicate optimal conditions for the species, whereas lower values indicate poor conditions. Geographically explicit and integrated studies of field observations, remotely sensed land-cover data, and other environmental data to estimate species distributions are an important application of the geographical sciences. SOURCE: Gillespie et al. (2008).

Geographical science approaches also contribute to the development of models that estimate potential biodiversity and aid in the development of conservation strategies on the basis of measured environmental parameters, human land-use patterns, species physiology, and species behavior. Coupled field and remote sensing modeling is being developed to estimate biodiversity over wide geographical areas. These approaches show much promise for documenting current conditions and establishing conservation strategies (Figure 2.5).

Understanding the geographical and environmental distribution of genetic diversity within species is necessary to anticipating how changes in population genetic structure could influence ecosystem functioning, extinction risk, and biodiversity (Reusch et al., 2005). As environmental changes affect a species, certain genotypes may be advantaged, and the genetic diversity of the species may change over time. Losses in genetic diversity can also occur through stochastic processes when species populations are isolated or become very small. The loss of genetic diversity may hamper a species' ability to exist in certain environmental settings because the genetically controlled traits required for survival in those environments have been lost. Understanding and preserving the genetic diversity of species, which often demonstrates spatial patterning, are important components of the conservation applications of the geographical sciences in the future.

What are the spatiotemporal patterns and drivers of ecosystem and habitat loss?

The rates of global ecosystem loss and habitat fragmentation and the relationship of those processes to biodiversity loss are important topics of continued research for the geographical sciences. It can be difficult even to compare fragmentation measures from one country to another because of differences in data availability and the metrics used (Kupfer, 2006). Some of the most important insights into the magnitude, rate, and spatial distribution of habitat loss have come from the geographical sciences. A recent study of Amazonian deforestation in Brazil by Morton et al. (2006) provides an informative example (Figure 2.6). Between 2001 and 2004 more than 3.6 million hectares of Amazonian forest were cleared for intensive agriculture. Morton and colleagues used a time series of MODIS (Moderate Resolution Imaging Spectroradiometer)

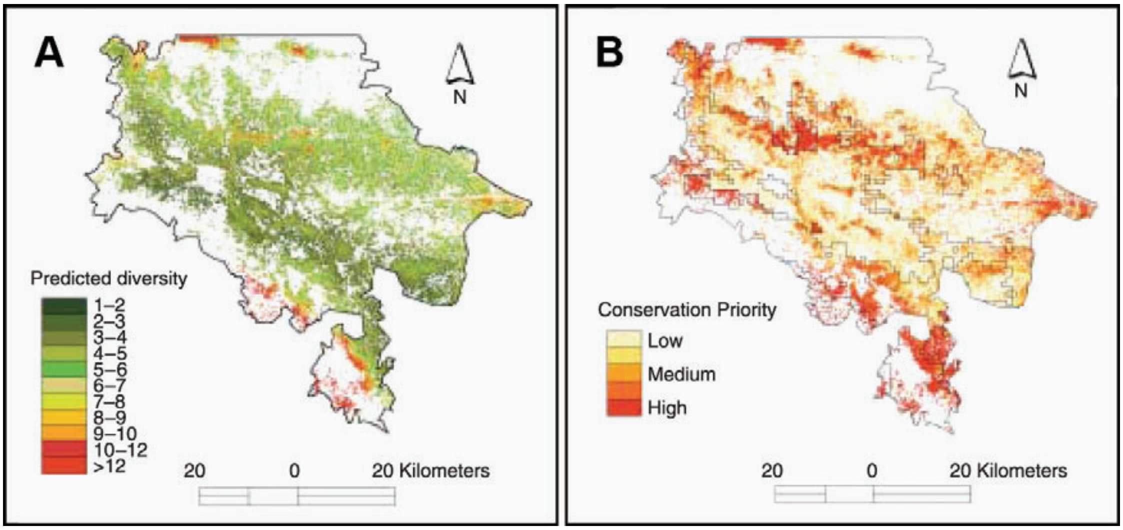


FIGURE 2.5 (A) Predicted tree species diversity and (B) suggested areas of conservation priority for the state of Chiapas, Mexico, based on combination and modeling of vegetation data, environmental data, human population and land-use data, and remote sensing imagery. Even in a highly fragmented and mountainous landscape, this research demonstrates the usefulness of integrated and spatially explicit approaches to documenting biodiversity and developing conservation strategies. SOURCE: Cayuela et al. (2006).

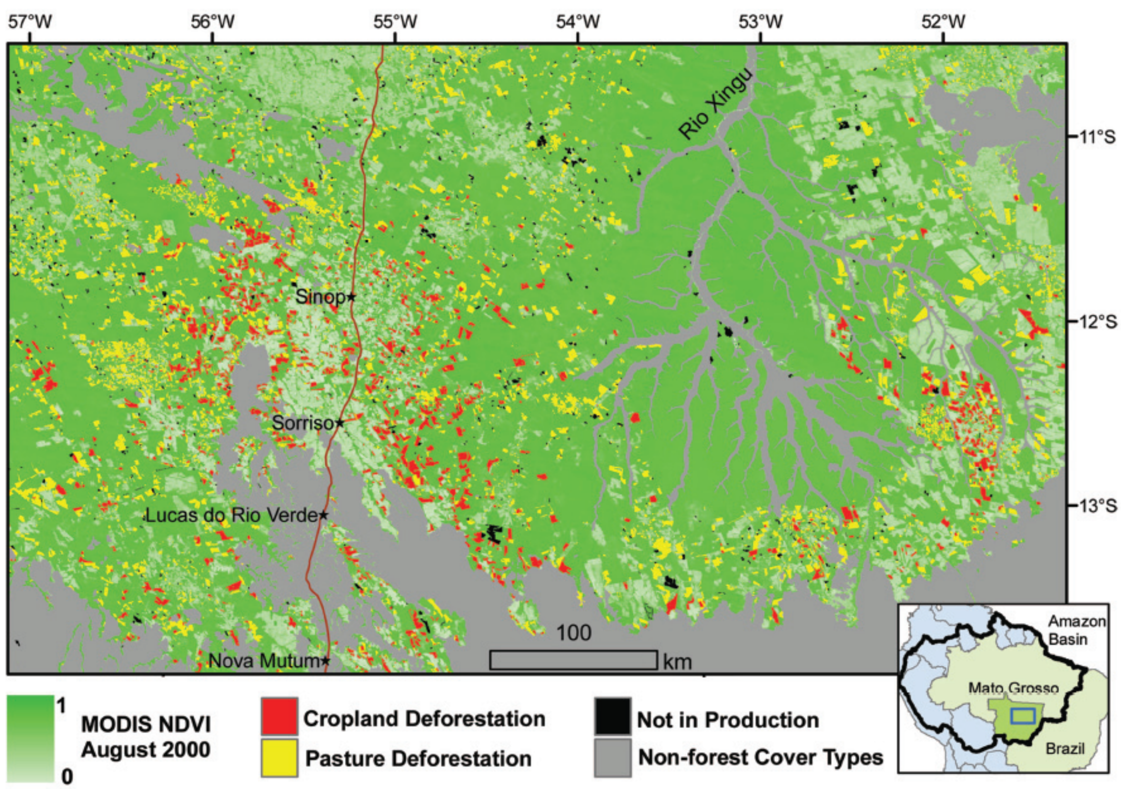


FIGURE 2.6 Clearance of Amazonian forest for pasture and cropland development in the state of Mato Grosso, Brazil, between 2001 and 2004 as detected from satellite imagery. Areas that were cleared for grazing were typically twice the size of patches cleared for crops. SOURCE: Morton et al. (2006).

satellite imagery to show significant deforestation caused by the clearing of more than 540,000 hectares for the development of both cropland and grazing land in the state of Mato Grosso, Brazil. They found that the destruction of forest land was not random. The satellite imagery showed that it occurred along the leading edges of previously cleared land. The study concluded that agricultural intensification and the development of permanent croplands and rangelands was accelerating rates of deforestation, and these rates might be expected to increase if crop prices rise in the future.

Habitat loss can further isolate current protected areas and make the conservation of species and ecosystems within such protected areas difficult. Morton et al. (2006) used 20 years of satellite data to assess changes in habitat around 198 of the world's largest tropical forest conservation areas. They found that about half of the protected areas had experienced significant natural habitat loss (i.e., 5 percent or greater) over the past 20 years. In some cases the loss of natural habitat in the surrounding buffer areas was as high as 80 percent. The increasing isolation of these protected areas makes them less effective as conservation areas for maintaining species diversity. There is great potential to expand the scope of such studies to many different world regions and timescales.

Although the biophysical sciences and remote sensing can do much to aid in biodiversity and ecosystem conservation, understanding the underlying socioeconomic patterns and forces that drive particular land-use patterns and ecosystem losses requires close interaction between biophysical and social scientists. Gap analysis, which uses GIS to overlay threatened species distributions, their habitat types, human land use, and the status of legal protection for lands can be extremely useful for determining geographically based conservation strategies and land acquisition priorities to preserve biodiversity in an increasingly fragmented environment (e.g., Davis et al., 2004; Gleason et al., 2006).

Two challenges for integrating sociocultural measures of land-use and land-cover change deserve particular attention in the coming decade. First, remote sensing data do not provide direct measures of sociocultural variables such as income, political preference, and education, only indirect, or proxy, measures. This limitation of remotely sensed data means that scientists attempting to explain land-surface or coastal ecosystem processes need to assert a relationship between the remotely sensed data and underlying social processes only when an externally validated link between the remotely sensed data phenomenon and the social process has been established. Thus further research on where and when to establish such links is needed.

Second, and linked to the first challenge, data from most remote sensing datasets, such as Landsat satellite imagery, are typically too coarse to provide effective measures of the small-scale or diffuse land-use and land-cover processes under examination. Fortunately, in recent years the availability of data that have finer spatial resolution has increased, and the cost has decreased. Geographical scientists are thus in a good position to test and improve, where possible, the explanatory power of recent research on land-use and land-cover change using increasingly finer resolution data.

How will future climate change influence species' distributions and biodiversity?

Information on climatic controls on geographical distribution and potential rates of species migration are critical to anticipating the impacts of future climate change on species. The climate and ecosystems of some present biodiversity hotspots may be so altered in the future as to make them unsuitable to support their current endemic species. Data are still too sparse, however, to predict confidently the impacts of climate change on future potential distributions and migration rates of most threatened species (Araújo et al., 2005; Pimm, 2007). Developing effective conservation policies depends on being able to predict where species will be able to exist under a changed climate and how fast they might be able to migrate to new regions as the climate changes. GIS-based collations and analyses of species distributional data and current and projected environmental conditions can be particularly important in linking field observations, climate forecasts, and ecological models of species distributions and potential migration rates in a spatially explicit manner to help with this task (e.g., Guisan et al., 2006). In terms of potential migration rates, the geographical sciences can contribute through both empirical studies based on observations of past and present organism dispersal patterns (e.g., Clark et al., 1998; Greene et al., 2004) and through mathematical simulations of dispersal (e.g., Malanson, 2003).

One example of a geographical approach to this problem—and a sobering view of the possible magnitude of climate change impacts—comes from a study by Malcolm et al. (2006). They examined 14 different computer models that produce estimates of the climatic changes likely to be caused by a doubling of CO_2. They averaged the climatic estimates produced by those models and used the averaged estimates of climate as input for two different models that predict biome distributions on the basis of climatic conditions. They then used these results to predict the possible future shifts of major biodiversity hotspots based on the predicted shifts in climate and vegetation. They then considered potential migration rates of the biota in the current hotspots relative to where suitable habitat for those species would be found in the future. They concluded that the extinction rates resulting from geographical shifts in current hotspots would be regionally variable, ranging from less than 1 percent to 43 percent, with an average loss of 11.6 percent of the species. They found that the most vulnerable hotspots were the South African Cape Floristic Region, Caribbean, Indo-Burma, Mediterranean Basin, Southwest Australia, and Tropical Andes (see Figure 2.1). In these areas, plant extinctions could exceed 2,000 species. A particularly troubling conclusion from this study was that if these climate-driven changes occurred within the projected time frame of 100 years, the rate of tropical extinctions caused by global warming could well exceed the already high rates of extinction from deforestation and land-surface change.

Observational records of plant and animal populations and ecosystems are usually too short in duration to detect and interpret long-term trajectories or the response of biological systems to long-term environmental change. Extending the temporal depth of environmental analysis along with the spatial coverage is a central concern of the geographical sciences. Such paleoecological and paleoclimatic studies can provide empirical data on the response of species in terms of geographical distribution, population size, migration rates, and extinction by looking at the fossil records of species and community reactions to past episodes of climatic warming over the Quaternary Period and earlier (Botkin et al., 2007; Willis et al., 2007; MacDonald et al., 2008a). Such research can point out which species or communities may be relatively resilient and which may be more sensitive to future land-surface and climate change based upon their response to past episodes of environmental change.

Paleostudies entail reconstructing long histories of ecosystems to indicate their response to past environmental changes and the degree to which they have been altered by human activity in order to provide benchmarks or targets for ecosystem restoration. An example of such a study comes from the work of Millspaugh et al. (2000) based on analysis of a sediment core from Cygnet Lake in Yellowstone National Park (Figure 2.7). Through the analysis of fossil charcoal and pollen Millspaugh et al. (2000) showed that there was a positive relationship between fire frequency and increased temperatures and aridity. The hot and dry conditions were natural variations in climate caused by increased summer insolation related to changes in the orbital geometry of Earth. These results suggest that increased fire frequency is a reasonable expectation with future climate warming, but that there is a high degree of adaptation and resilience to varying fire frequencies in the vegetation of Yellowstone. Both observations are important for the management of the Park's ecosystems in the face of climate change. More basic biogeographical research on species distributions, environmental relations, and dispersal capabilities, coupled with model development, can improve assessments of the impacts of climate change on biodiversity and endangered ecosystems.

How can we conserve biodiversity and ecosystems while sustaining human livelihoods?

Devising conservation strategies requires grappling with the complexity in indigenous as well as increasingly globalized land-use practices and differing cultural approaches to nature valuation, conservation practices, and compliance (e.g., Messina et al., 2006; Robbins et al., 2006; Walsh et al., 2008). The role of socioeconomic factors in habitat ecosystem modification and biodiversity is often complex and at times counterintuitive. Geographical scientists working at the interface of conservation ecology and the social sciences have shown, for example, that some human land-use patterns, such as certain forms of swidden

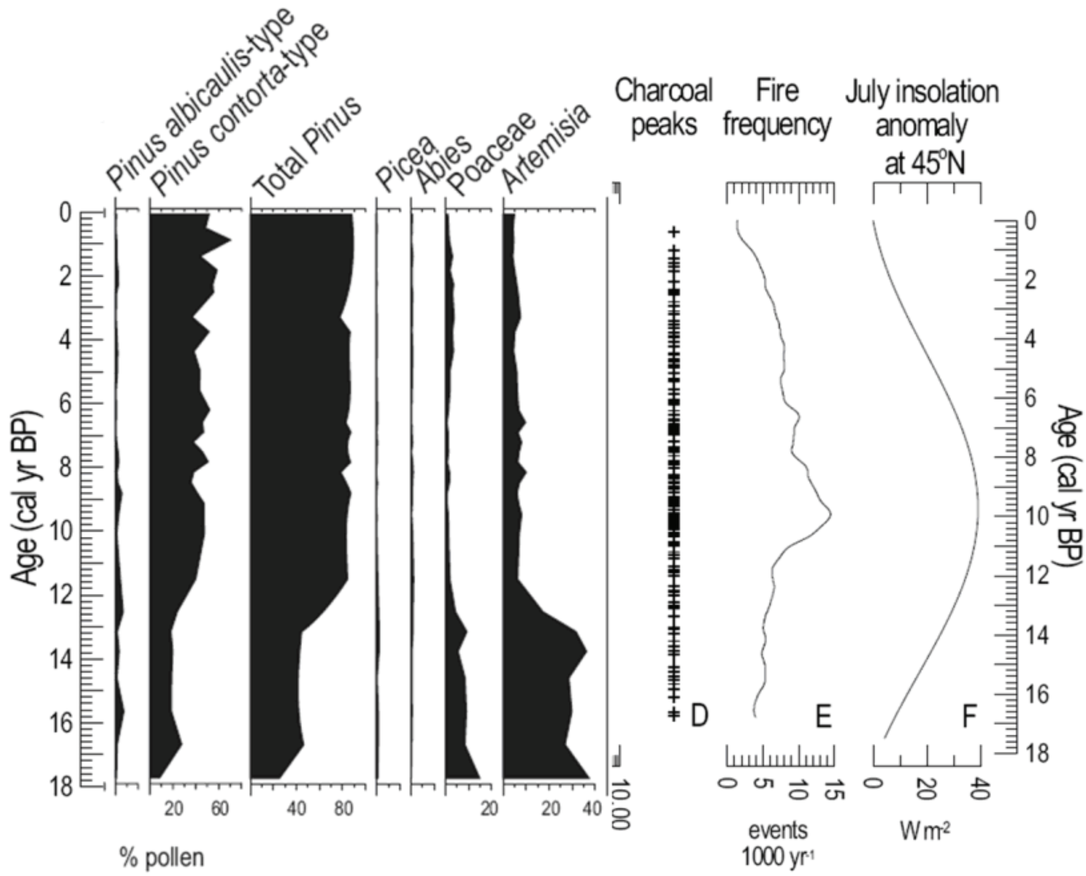


FIGURE 2.7 The history of regional vegetation and fire frequency in Yellowstone National Park over the past 17,000 years based on fossil pollen and charcoal. Since 11,000 years ago the vegetation has remained relatively stable despite significant long-term changes in fire frequency driven by climate change related to changes in July insolation related to changes in Earth's orbital geometry. SOURCE: Millspaugh et al. (2000).

agriculture,[2] may support local human populations and also serve to mimic natural disturbance regimes and thus help preserve biodiversity (Robbins et al., 2006; see also Chapter 5).

The geographical sciences have contributed to current debates about the premises behind widely used conservation strategies such as the best approach for ex situ biodiversity conservation.[3] Although the concept of the modern park, or "Yellowstone model," dates to the late 19th century, the related notion of a hunting preserve took form across the tropics during the colonial era (Cronon, 1996). These preserves endured over time, eventually becoming national parks that gained considerable international support following the rise of an environmental movement in high-income countries during the 1970s and 1980s. By the late 1980s, however, it was becoming clear that the park model was failing in many tropical countries. In most cases there was

[2]Swidden agriculture is the practice of clearing relatively small patches of forest through cutting and burning and then cultivating crops for a short period—typically 3 to 5 years—until soil nutrients decrease. The plot is then withdrawn from cultivation and secondary forest succession is allowed to occur. After several fallow years during which soil nutrients are restored, the forest on the patch is again cleared and the land cultivated. The practice produces a landscape with a diverse spatial pattern of cultivated fields and patches of forest of various ages, structure, and species composition.

[3]Ex situ biodiversity conservation is the maintenance of endangered species at areas outside their natural ranges or habitats. Examples include the preservation of an animal species population in a zoo or wild animal conservation areas or the preservation of a plant species population in a botanical garden.

a strong conviction that local people were destructive agents who should not live within the borders of parks (Cronon, 1996). This notion led to the removal of local peoples and the near or complete destruction of their livelihoods, in the process straining relations between park authorities and local residents (e.g., Peluso, 1993; Guha, 1997).

The failure of the park model led to a dynamic round of experimentation with community-based natural resources management (CBNRM) starting in the late 1980s. Here the core idea was that the government needed to give local people a stake in the success or failure of a park. The theory was that if local people profited from ecotourism, they would actively support efforts to conserve wildlife within and around the borders of a park. Associated with this flurry of experimentation was scholarship championing this approach (e.g., Metcalf, 1994) as quite positive whereas others, most notably Neumann (1997, 2002), saw CBNRM—and related approaches such as buffer zones—as just another disguised extension of a park model that ultimately constrained the livelihoods of local people. Still others saw the way in which CBNRM was implemented by governments as the major problem (e.g., Logan and Moseley, 2002).

By the late 1990s, there was a group of conservation biologists—most notably Terborgh (1999, 2000)—arguing that CBNRM had completely failed to conserve biodiversity and that there should be a return to a stricter and more robust form of the park model, sometimes referred to as fortress conservation. Subsequent scholarship critiqued the reemerging fortress conservation model, questioning whether it really served to conserve biodiversity (Robbins et al., 2006) and pointing out that it was still devastating for local livelihoods (Wilshusen et al., 2002). These studies highlight a growing body of work in the geographical sciences that underscores the importance of incorporating local perspectives and ideas in the development of biodiversity and ecosystem conservation strategies (Stevens, 2002; Kates et al., 2005).

Confronting these issues from an integrated natural and social sciences perspective is a major challenge that calls upon the integrative perspective and analytical tools of the geographical sciences (e.g., Turner et al., 1995; Liverman et al., 1998; Lambin et al., 1999; Fox et al., 2002; Walsh and Crews-Meyer, 2002). These integrated approaches are in the early stages of being formally incorporated into LCS (Turner et al., 2005, 2007) and should be examined for inclusion in the specific context of biodiversity and ecosystem conservation.

SUMMARY

Lessons learned by geographical scientists in the past two decades from attempts to model the process of land-use and land-cover change, and to project future distributions of land use and land cover, suggest that socially sensitive and integrated research approaches within the geographical sciences could greatly assist in the development and implementation of viable conservation strategies (e.g., Pontius et al., 2007). The ability of the geographical sciences to combine field studies, remote sensing data, climate data, and land-change models to understand ecosystem changes and biodiversity distribution will be critical to developing land-use policies and conservation strategies in the coming decade.

3

How Are Climate and Other Environmental Changes Affecting the Vulnerabilities of Coupled Human–Environment Systems?

The biophysical changes unfolding across Earth's surface are of increasing concern. Yet earth systems have always been changing and life has survived many environmental perturbations, a reflection of both biological adaptation and human ingenuity. It is thus important to view current biophysical changes not so much as raising issues of survival, as of creating differential vulnerabilities. Which life-forms are likely to be most exposed to, and negatively affected by, environmental changes? Are there significant socioeconomic changes unfolding alongside environmental changes that could leave some people or ecosystems with much greater exposure to risk? In such cases, will vulnerabilities associated with socioeconomic changes likely amplify or attenuate the impacts of environmental changes? Do some people or environments cope better with the impacts of changing circumstances than others?

The preceding questions treat people and their proximate biophysical environments as a unit—a coupled human–environment system (Turner et al., 2003b)—rather than as separate systems (cf. NRC, 1992).[1] Such questions are geographical because the vulnerability of coupled human–environment systems—and, by extension their resilience (e.g., Berkes et al., 2002) or sustainability (e.g., Kates et al., 2001)—is a function of geographical differences in exposure, sensitivity, and adaptive capacity (Smit et al., 1999; McCarthy et al., 2001; Turner et al., 2003a; Gallopin, 2006). A fundamental concern of vulnerability, resilience, sustainability, and adaptation studies is to understand the conditions under which some places may be harmed by a given environmental change, even as others emerge relatively unharmed or in a better position to withstand repeated events in the future.[2]

Consider the Hurricane Katrina example discussed in Part I of this report. Geographical questions about vulnerability are critical to understanding what happened and to reducing associated risks in the future: Which people were, and were not, exposed to the breached levees and associated rising water levels, and why? Were all neighborhoods near breached levees equally sensitive to the rising water (e.g., did some of the exposed neighborhoods experience lesser physical and financial impacts than other exposed neighborhoods)? Of the exposed and sensitive places, which groups and individuals were able to adapt, restore their previous livelihoods, and/or reduce exposures and sensitivities to future storms? Raising and answering such questions is critical if some of the mistakes made leading to and in the aftermath of Hurricane Katrina are to be avoided in the future (Kates et al., 2006).

[1]Several terms have been used to refer to coupled human–environment systems, including coupled natural–human systems (e.g., NSF AC-ERE, 2003), coupled human and natural systems (e.g., Liu et al., 2007), and socioecological systems (e.g., Berkes and Folke, 1998).

[2]Vulnerability assessments address the same general problems as inquiries into resilience (the ability of systems to cope with perturbations; see, e.g., Holling, 1973; Berkes and Folke, 1998) and sustainability (the long-term viability of systems, e.g., World Commission on Environment and Development, 1987; Kates et al., 2001). The extent of conceptual overlap among these three concepts varies depending on how the concepts are defined (Kates, 1985; Gallopin, 2006), but the concept of vulnerability speaks to key aspects of resilience and sustainability, because vulnerable coupled human–environment systems are, by definition, less resilient and less sustainable.

Understanding vulnerabilities associated with discrete events such as Katrina can illuminate more general vulnerabilities and associated adaptation options and constraints that are tied to long-term changes in climate. Climate change is expected to produce changes in patterns of precipitation and water availability (Figure 3.1), but it is unclear what vulnerabilities these changes may produce without first assessing how sensitive local populations are to such changes, and how effectively people may respond to the impacts of the changes. It is also important not to focus so much attention on climate events that we lose sight of how coupled human–environment systems may be vulnerable to nonclimate stresses or perturbations. A variety of natural occurrences and social processes can increase the vulnerability of peoples and places, including tsunamis, earthquakes, droughts, toxic waste spills, nuclear contaminations, economic globalization, deforestation, and HIV/AIDS. Complicating matters further is the fact that these developments do not necessarily operate in isolation, and that some of them (e.g., economic globalization) present potential benefits as well as pitfalls.

ROLE OF THE GEOGRAPHICAL SCIENCES

Since the 1980s, global environmental change has emerged as an important research area in many academic disciplines. Geographical scientists have played major roles in a variety of international and interdisciplinary environmental-change initiatives, and have taken a leading role in bringing vulnerability issues to the fore. Their research draws on a rich tradition of geographical work concerned with how humans are transforming Earth (Marsh, 1864; Sauer, 1925; Thomas, 1956; Glacken, 1967; Turner et al., 1990a). The approach of the "Chicago School of environmental risks and hazards" has been particularly influential. The Chicago School is based on the pioneering work of Gilbert White (e.g., White, 1945), who sought to explain why, in early 20th century United States, aggregate flood-related damages were rising, not falling, despite expanded technological interventions aimed at reducing flood damage. To answer this question, White focused on people's decisions, asking what informational or psychological limitations led people to approach environmental risks and hazards in a way

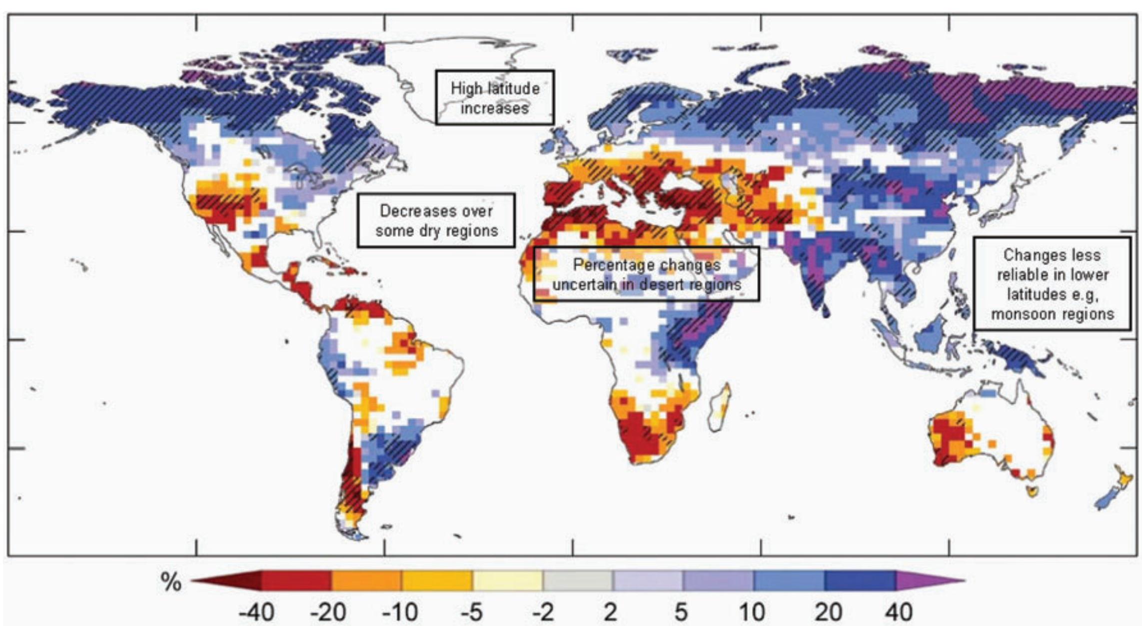


FIGURE 3.1 Global map of projected changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the Special Report on Emissions A1B scenario. White areas are where less than 66 percent of the 12 models agree on the sign of change, and hatched areas are where more than 90 percent of the models agree on the sign of change. SOURCE: IPCC (2007).

that produced suboptimal outcomes (cf. Burton et al., 1978).

Several recent major global research initiatives have grown out of the Chicago School's concern with the risk–hazards relationship, including sustainability science (e.g., Kates et al., 2001), socioecological resilience studies (e.g., Berkes and Folke, 1998), adaptation science (e.g., Smit et al., 1999), and coupled human–environment system vulnerability studies (e.g., McCarthy et al., 2001; Turner et al., 2003b). These four intersecting agendas define the core vulnerability-related research domains to which the geographical sciences are currently contributing. The contributions of the geographical sciences have focused particularly on understanding how people (and ecosystems) produce, and respond to, changing environmental conditions (e.g., Dow, 1992), and the social and political processes that produce differential exposures, sensitivities, and adaptive capacities, even in the absence of changing environmental conditions (e.g., Wisner et al., 2004).

A geographical perspective on vulnerability exhibits five basic features (Schröter et al., 2005). First, geographical studies of vulnerability situate the unit of analysis within the coupled human–environment system, rather than solely within the human or the environmental system. Accordingly, the methodological basis for these studies tends to be interdisciplinary, involving not only researchers from different academic backgrounds, but also stakeholders (i.e., those involved in making decisions about the processes under consideration). Second, the scale at which the coupled human–environment system is studied is generally "place-based," meaning that local-scale human–environment processes and outcomes are emphasized—although not to the exclusion of processes and outcomes at other scales. Third, because the general unit of analysis is the coupled human–environment system, the drivers of system change are understood to be multiple and possibly interacting. Fourth, the analytical concern with exposures and sensitivities of multiple systems to multiple stressors at multiple scales means that central attention is given to the differential abilities of places to adapt to stresses. Finally, recognition of the dynamic nature of the interactions that shape coupled human–environment systems translates into a concern with shifting vulnerabilities across time (how vulnerabilities have changed in the past and what they might look like in the future). What unites these five characteristics of geographical vulnerability studies is that the particular interconnections among processes found in different places are privileged rather than assumed away.

Two recent studies illustrate what the geographical sciences bring to the study of vulnerability. In one study, Cutter and Finch (2008) analyze temporal and spatial changes in social vulnerability via the Social Vulnerability Index (SoVI), which measures the social vulnerability of U.S. counties to environmental hazards (originally introduced in Cutter et al., 2003). The SoVI is a score assigned to each unit of analysis (in this case, U.S. counties) derived from a principal components analysis of variables hypothesized to reflect various social vulnerabilities to natural hazards. Cutter and Finch draw on decennial U.S. Census data for the period 1960-2000, but their study is also forward looking. They examine trends in the historic data to project SoVI values for the year 2010, and they compare maps of SoVI scores for each past census year with the projected year (Figure 3.2). Future vulnerability studies of this sort could benefit from data at a finer spatial resolution (in some parts of the country, the county represents areas that are so large and populous as to mask important local variations), and from data reflecting the effects of multiple hazards in a given location. These types of data could be correlated with the SoVI; stakeholders could also be polled to comment on the utility and accuracy of the model results.

A second study by O'Brien et al. (2004) illustrates an approach to studying vulnerability that treats it as the product of multiple interacting stressors. Their case study looks at the interrelated vulnerability impacts of globalization and climate change in India (see also the discussion of this line of research as it relates to inequality, in Chapter 8). They collected secondary data reflecting multiple biophysical, social, economic-trade, and technological features of individual Indian districts, and analyzed the data using geographic information system (GIS) map algebra. This approach allowed them to produce a set of district-level maps of exposures, sensitivities, adaptive capacities, and vulnerabilities that highlighted districts that are doubly exposed to the negative impacts of globalization and climate change (see Figure 8.4). The authors further sampled three of these doubly exposed districts for further in-depth

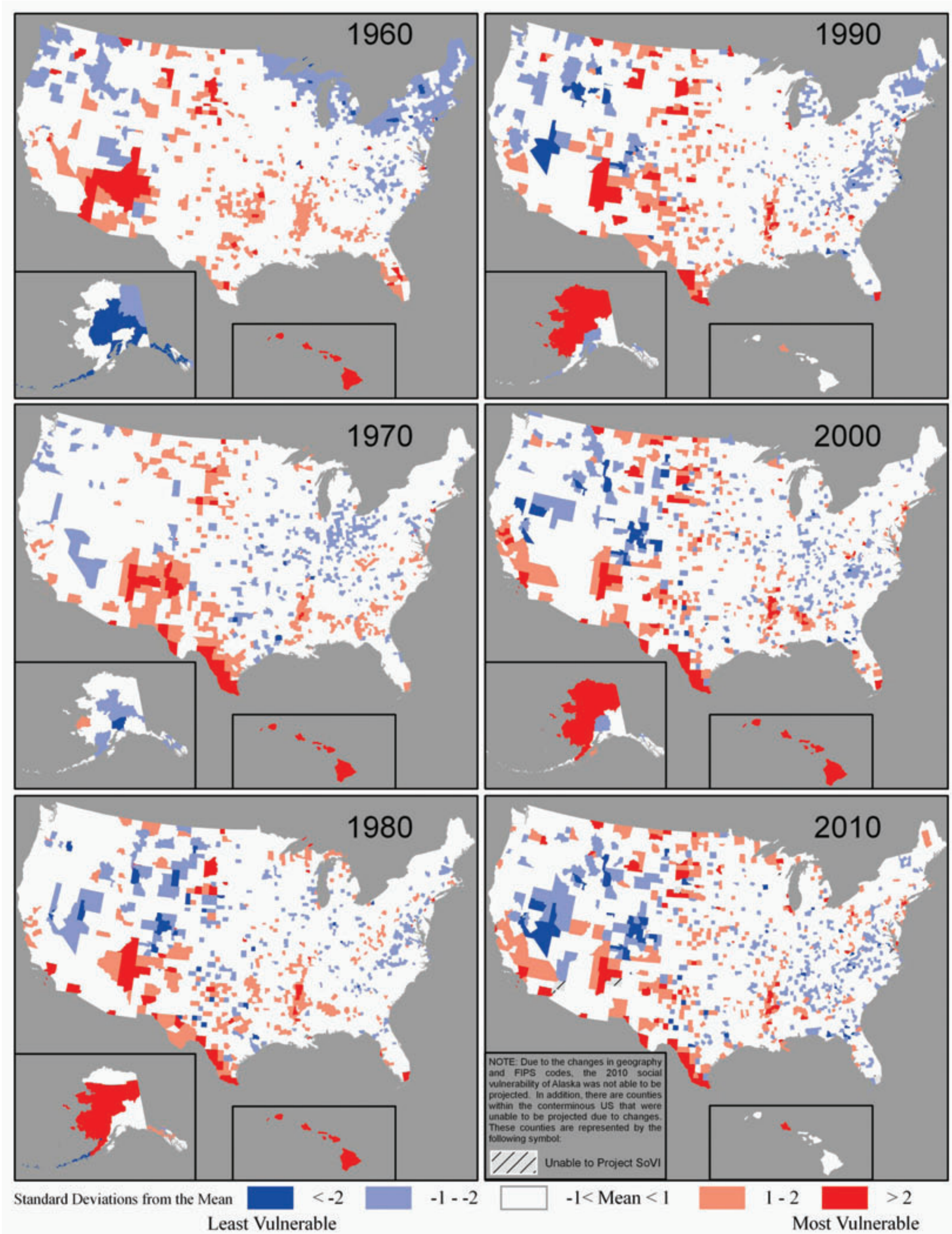


FIGURE 3.2 Maps from the Social Vulnerability Index (SoVI) illustrate the results of bringing the geographical science perspective to the study of vulnerability. SoVI scores are place-based because, by construction, a county's SoVI score is only meaningful in relation to an entire set of county scores. When the scores are mapped, they illustrate the geographical variation in social vulnerability, and highlight potential uneven capacity for disaster preparedness and response. The scores can be used by both policy makers and practitioners to determine resource allocation for disaster preparedness. SOURCE: Cutter and Finch (2008).

local examination, using participatory rural appraisal techniques, including surveys and interviews. Future vulnerability studies could benefit from a sensitivity analysis to elucidate the relative importance of different stressors in producing vulnerability. Such studies should also consider how legal and administrative realities may be amplifying or attenuating the components of vulnerability.

As the foregoing examples suggest, the geographical sciences approach to vulnerability recognizes that

vulnerabilities are dynamic across space and time, and are most meaningfully examined at a local scale, provided larger-scale influences are not ignored. The geographical science approach to vulnerability engages not only expert scientists, but also other people who belong to and know intimately the peoples and places under study. Research advances are likely to come from investigations that both fill in gaps in our understanding of particular places and address questions of resilience, sustainability, and adaptation. The following illustrative subquestions provide examples of the types of research that would be particularly productive to pursue.

RESEARCH SUBQUESTIONS

How will climate change affect patterns of vulnerability and resilience in rapidly urbanizing areas?

Human land uses and land-use changes are implicated in global environmental change and resulting patterns of vulnerability (Turner et al., 1990b; Rindfuss et al., 2004; Foley et al., 2005). Yet the precise links between land-change processes and vulnerability are not well understood (Turner et al., 2005, 2007). Most land-change research has underemphasized one or more of the five criteria for vulnerability assessments outlined above, and has focused on a specific type of land change (typically forest conversion for harvesting, agricultural, ranching, and/or settlement purposes) in a specific type of setting (often tropical or subtropical locations) (e.g., Moran et al., 1994; Rudel, 2005). The extraordinary growth of cities in the contemporary era, however, points to the need for land-change research using a vulnerability approach in rapidly urbanizing locations.

Coastal zones are important sites for research because many of them are urbanizing rapidly and will likely face impacts from climate change (Chapter 4). Will rapid urbanization render coastal ecosystems particularly vulnerable to the effects of sea-level rise and tropical storms in the 21st century? How will people's culturally driven preferences for certain types of urban vegetation, such as turfgrass, affect urban coastal ecosystems? Most important, how will these coupled human–environment systems respond and adapt to shifting exposures and impacts? Efforts to address these types of questions can build on recent geographical research linking urbanization and environmental change in different settings. Researchers in Phoenix, Boston, New York, and Baltimore have examined, in parallel efforts, the spatial relationships among changing urban land uses and land covers and a variety of human–environment outcomes (Guhathakurta and Gober, 2007; Kirshen et al., 2008; Boone et al., 2009; see also, e.g., Law et al., 2004; Rosenzweig et al., 2005; Ruth et al., 2006).[3] These research projects, which are diverse in methodological approach, could be expanded through a coordinated effort to examine the human–environment impacts of land-use and land-cover changes under different climate change scenarios, and by focusing not only on physical outcomes, but on social response options and constraints.

The extent to which urbanizing areas in general, and urbanizing coastal zones in particular, will be vulnerable to the effects of climate change will depend not only on the range of technological and policy options, but also on the feasibility of implementing those options. Feasibility is, of course, a function of cost, but cost is not the only constraint. Political, social, and cultural barriers and opportunities may also be important in the decision-making calculus. To identify the presence or importance of such opportunities and constraints, research needs to be undertaken that is aligned with the needs of decision makers—both individual citizens and people in positions of authority (e.g., infrastructure managers, elected officials). The prospects for such alignments grow when the science is coproduced with the potential end users of the research—an undertaking that is not simple and usually requires a sustained relationship-building effort among the different constituencies (White et al., 2008; Gober et al., In Press).

The conceptual frameworks, theoretical bases, and methodological approaches employed in tropical land-change research may need to be adapted for use in examining the land-change–vulnerability link in urbanizing zones.[4] Data are needed that can facilitate

[3]These studies have looked at a wide range of variables including water use, urban heat islands, natural resource decision making, urban infrastructure management, flooding, vegetation type, crime, social capital, hydrological flows, and nitrogen cycling.

[4]One reason tropical deforestation studies may not be directly transportable to the urban coastal context is that most of the tropical studies are set in low-income, primary-economy settings, whereas many of the urbanizing coastal zones are in relatively high-income, tertiary-economy, or residential settings.

analysis of the interconnected impacts of urbanization and climate change on local hydrological flows, nutrient concentrations, flora and fauna, and human health. In urbanizing coastal zones, research is also needed on land-change–vulnerabilty links, including studies of estuarine eutrophication and associated impacts on marine-related livelihoods (e.g., fishing, tourism) and assessments of the prospects for different mitigation strategies (e.g., of reducing nitrogen inputs into streams). A key overarching concern should be the trade-offs that people are likely to face in different places as environmentally destabilizing climate change becomes more acute.

Answers to these questions can advance scientific understanding and address management and policy needs. Effective decisions require data on the full suite of human and environmental variables implicated in these human–environment processes: household-level data on individual characteristics, attitudes, and behaviors; community-level data on general governance structures and specific land and resource management policies; and state-level data on economy and society. Using GIS, for example, social variables can be examined spatially alongside environmental variables (e.g., land cover, climate, hydrology, topography). The types of research teams needed to collect and analyze such data are similar to those participating in several past, current, and future interdisciplinary research programs supported by the National Science Foundation, the U.S. Forest Service, and NASA, such as Coupled Natural-Human Systems, Decision Making Under Uncertainty, Human and Social Dynamics, Long-Term Ecological Research, Urban Long-Term Research Areas, and Research Opportunities in Space and Earth Sciences. Like the work being done under the aegis of those programs, the tools and techniques of the geographical sciences are essential to the task of integrating the data that need to be analyzed across space and in particular places.

How can we better measure and integrate the impacts of processes operating at different scales on vulnerability and resilience?

As noted in Part I, scale is a bedrock geographical concept. Geographical scientists have shown that the relationships observed at one scale do not necessarily mirror those observed at other scales. This idea is well established in general terms (Meyer et al., 1992; Bian and Walsh, 1993; Easterling, 1997; see also, e.g., Moellering and Tobler, 1972; Openshaw and Taylor, 1979; O'Neill, 1988; Root and Schneider, 1995), and particularly in the land-change literature (e.g., Geoghegan et al., 1998; Lawrence et al., 2005). Yet to date, there have been few vulnerability studies in which multiple, nested scales are analyzed simultaneously (cf. O'Brien et al., 2004, for an exception). Moreover, there have been no systematic attempts to pool existing vulnerability results from varying scales to produce generalizations about scale dependencies, a challenge discussed in the next illustrative subquestion. For example, for the municipality of New Orleans, were Katrina-related vulnerabilities at the household level significantly associated with municipal-level land-use policies? If so, were these relationships more important in certain neighborhoods than others?

To advance understanding of cross-scale vulnerability dynamics, two historical obstacles need to be confronted: (1) the lack of availability and high cost of high-spatial-resolution data and (2) inadequate resources for processing those data (see discussion in Part III). For vulnerability studies requiring land-cover information, assessing household-level processes has been limited by the spatial resolution of satellite imagery, often with pixels that are 30 m on a side (i.e., 900-m^2 areas). This level of resolution does not allow direct statements to be made about individual household-level processes and outcomes when, as is common, multiple households are collocated within a given 900-m^2 area. For those cases where high-resolution data have been available and affordable, the resources required to process the data—for broad geographical extents—has represented another research obstacle. Processing high-resolution aerial photographs (i.e., <1 m) has been prohibitively expensive, even for municipal-scale studies.

In recent years, however, the costs of very high resolution imagery (i.e., with pixels <1 m) and the software required to process such imagery quickly have declined, and this trend is likely to continue. These cost reductions make it easier for researchers to use high-spatial-resolution data to examine processes and outcomes at multiple scales simultaneously. In the coming decade, our understanding of cross-scalar dynamics can be greatly enhanced if geographical scientists develop a

series of municipal-level vulnerability studies that draw from high-resolution environmental datasets that can capture the scale of the household. In this way, households need not be sampled from a given municipality, and a more representative picture can emerge of both household- and municipal-level processes.

Of course, remote sensing data represent only a subset of the potentially necessary data for the study of coupled human–environment system vulnerability and resilience. Other means of data collection and analysis (e.g., interviews, surveys, focus groups, participant observation) have proved valuable as well. Such methods can be effective for making observations about exposures, sensitivities, and adaptive capacities, at multiple scales. Indeed, the data generated by such approaches are often rich in information about cross-scale interactions, and can shed light on how the outcomes that are observable at one scale are associated with factors at other scales. Developing methods for assessing these cross-scale interactions would advance our understanding of the challenges faced by coupled human–environment systems. Building on past vulnerability studies that use a variety of data collection and analysis methods, and on geographical technologies that identify or estimate the variable impacts of multiple processes in individual places, the geographical sciences are well positioned to test the long-held geographical hypothesis that "scale matters" in the vulnerability domain.

How can studies of vulnerability and resilience on qualitatively different topics be compared to make valid broader generalizations about vulnerability?

Vulnerability and resilience assessments are wide-ranging. Some studies have examined agricultural dynamics in developing countries, whereas others have focused on urbanization challenges in Western Europe. The topical diversity of studies makes it difficult to draw comparisons and make generalizations from independent study results. To move forward, research is needed that can facilitate efforts to specify the general conditions under which coupled human–environment systems become vulnerable to the effects of human–environmental changes, document and assess the geographical patterns of these vulnerabilities, and analyze why such patterns emerge. If this challenge is not taken up, the vulnerability concept could evolve into an appealing idea with limited applied scientific value beyond providing spatially and temporally contingent findings from a set of noncomparable case studies.

It follows that a major research need for the coming decade is to inventory the existing vulnerability and resilience literature, and to determine whether the studies can be compared using a meta-analytic framework for the purposes of drawing broad conclusions about vulnerability—even when the data and the methods used to collect and analyze the data differ. There is a well-developed meta-analysis literature in the social sciences, specifying how to pool results from independent studies into a larger dataset that permits more powerful inferences and generalizations. Meta-analysis is most helpful and easiest when the predictor and outcome variables are similarly defined and measured. For example, medical studies of the effects of smoking on human health can be readily pooled because a person's smoking behavior and health are variables that lend themselves well to common definitions and measurements.

Extending classical meta-analytic techniques would be useful in the case of vulnerability, where the definitions and measurements of variables are often not comparable across studies. Geographical scientists have contributed to an allied effort in recent years, attempting to draw systematic comparisons across studies of tropical deforestation that look at different variables and employ diverse methods. Notable examples of such meta-analyses include Geist and Lambin (2002), Misselhorn (2005), and Rudel (2005). None of these applications, which use techniques such as qualitative comparative analysis (QCA; Ragin, 1987), address vulnerability as such, but they hold promise for vulnerability research. Research is needed to demonstrate whether a creative blending of techniques and methods (e.g., coupling QCA with the vulnerability scoping diagram [Polsky et al., 2007]) can facilitate the production of vulnerability meta-analyses. Geographical scientists are well positioned to contribute to this undertaking. They could pool results from the emerging body of knowledge on, for example, the land-use-policy/coastal-storm vulnerability relationship in the New Orleans area and test the applicability of the common themes that have emerged in that domain to other coastal-zone metropolitan areas exposed to similar environmental hazards (e.g., Miami, Houston).

SUMMARY

The geographical sciences recognize that vulnerabilities are dynamic across space and time. Opportunities to expand our understanding of the changing patterns of vulnerability in response to environmental change are most likely to come through research focused on underexamined contexts and through research that looks for patterns and processes across geographical spaces and scales. Advances in our understanding are most likely to be achieved through investigations that examine issues of resilience, sustainability, and adaptation at local scales, and their relationships to larger scale processes.

4

How and Where Will 10 Billion People Live on Earth?

We live in the century of the city. In 2008, humanity crossed a milestone as it marked the first time that more people lived in urban areas than any other type of settlement. The United Nations forecasts that most of the global population growth in the coming decades will occur in urban areas. World population is expected to increase by 1 billion to 5 billion between 2007 and 2050 (UN, 2009),[1] yielding a global total of between 7.9 and 12 billion people by 2050 depending on fertility and mortality trends (Figure 4.1).[2] Under the medium-growth scenario, world population will be almost 10 billion by 2050, with an estimated 3.1 billion new urban dwellers.[3] Notwithstanding uncertainties around the effect of HIV/AIDS and economic downturns on mortality and urban migration, the current scale of urbanization is unparalleled in history (Cohen, 2004).

An urbanizing global population has significant consequences—potentially positive as well as negative—for resource use, environmental sustainability, and ultimately, the well-being of humanity. The concentration of people and resources in dense urban settlements can reduce the energy consumed for buildings and transportation and can lower carbon dioxide emissions (NRC, 2009). Urban areas also provide economic opportunities and, in many places, are the engines of economic growth.

Most urban population growth will be concentrated in the developing world, particularly in Africa and Asia. Historically, urbanization has taken place primarily in more developed regions. In 1990, the populations of Europe, North America, Latin America, and Oceania were already more than 70 percent urban (Figure 4.2). In contrast, even by 2010, the urban population of Africa will barely approach 40 percent and Asia's urban population will be less than half of the total population.

In addition to an urbanizing population, globally, the number of households is growing faster than population (Liu et al., 2003). In the United States, the average household size has been steadily declining, from 5.5 in 1850 to 4.5 in 1915 to 2.56 in 2008 (U.S. Census Bureau, 2004). In particular, the proportion of the population living in single-person households has increased significantly, from 7.7 percent in 1940 to 25.8 percent in 2000. The resulting increase in the number of households relative to population growth poses significant threats to biodiversity and natural resources because per capita consumption of resources is more closely aligned with the number of households than with the population per se (Liu et al., 2003). Not only does each household maintain its own residence, but total per capita living space has been increasing in many countries. In the United States, the average size of single-family homes increased from 1,500 ft^2 (139 m^2) in 1970 to 2,519 ft^2 (234 m^2) in 2008, an increase of more than 60 percent (U.S. Census Bureau, 2004). Similarly, in China, per capita residential living

[1] United Nations Population Database, World Population Prospects, 2008 Revision. Available at www.esa.un.org/unpp/index.asp?panel=1 (accessed February 11, 2010).

[2] The high degree of variance reflects high levels of uncertainty in making population projections.

[3] The 0.6 billion difference between the increase in world population and urban population will be due to population growth occurring mainly in urban areas and rural to urban migration.

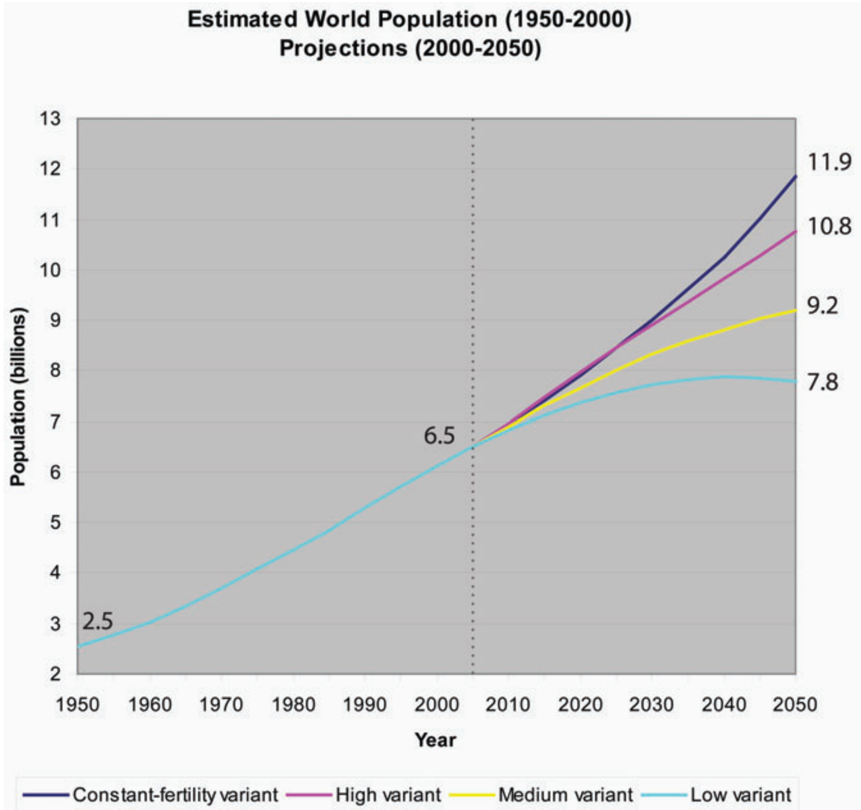


FIGURE 4.1 Depending on fertility and mortality rates, total world population could reach nearly 12 billion by 2050, but could be as low as 7.9 billion. SOURCE: United Nations.

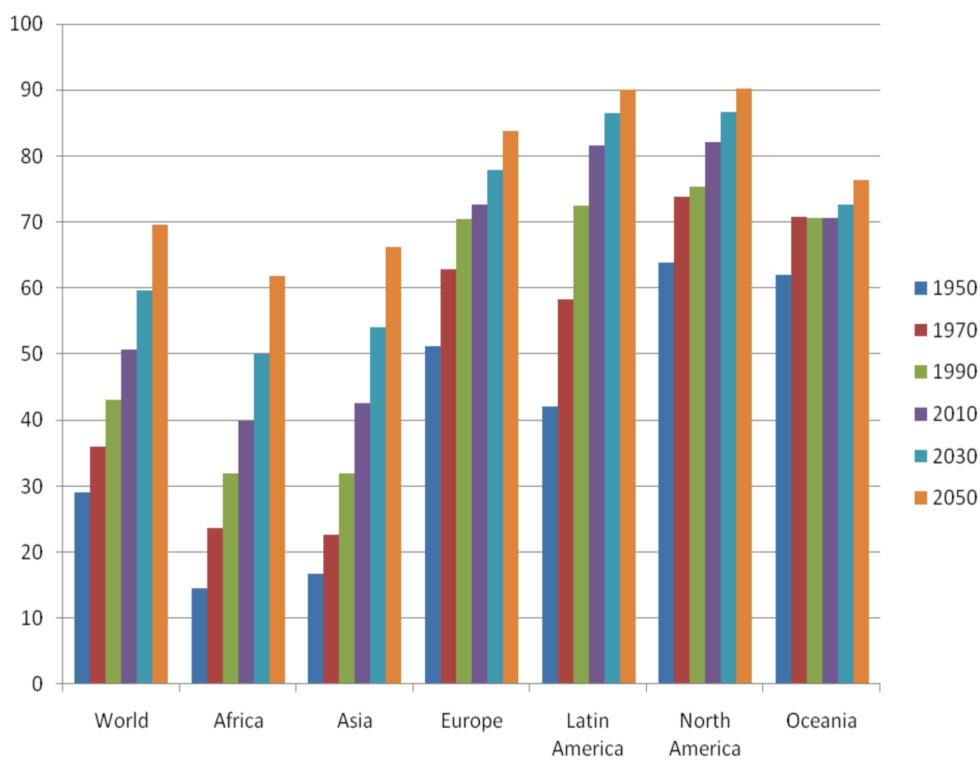


FIGURE 4.2 Percentage of urban population by region, 1950-2050. SOURCE: United Nations.

space has tripled over a 27-year period, from 8.1 m^2 in 1978 to 26 m^2 in 2005 (National Bureau of Statistics of China, 2009).

It follows that we need to understand how 10 billion people will be allocated among households and distributed geographically across the world over the next 40 years. What processes create diverse patterns of human settlement? How is accelerating urbanization changing social, environmental, and economic conditions? The environmental challenges, resource requirements, infrastructure needs, energy demands, and governance issues associated with the unfolding growth in urban population raise fundamental, policy-relevant questions—and pose unprecedented opportunities for moving toward sustainability—that cannot be ignored as society navigates the urbanizing world of the 21st century. Thus, one of the biggest challenges facing humanity is how and where 10 billion people will live so as to reduce their environmental footprint. Given that most of these 10 billion people will live in cities, what are the consequences of an urbanizing Earth, and how can we reduce the negative impacts, while enhancing the positive impacts?

ROLE OF GEOGRAPHICAL SCIENCES

The study of human settlements is inherently an investigation of human–environment interactions, which requires spatially explicit data and analysis, an understanding of the interaction among places and across scales, and knowledge of the trade-offs among different land uses. Studies of the city, urban growth, urban-land-use theory, and the development of human settlements all have long traditions in the geographical sciences (Marsh, 1864). Much of the work on urban areas, their form and function in urban planning, urban economics, urban geography, and urban sociology, has drawn on the spatial land-use models of von Thünen (1826/1966), Burgess (1925), Muth (1961), Alonso (1964), and others.

Although cities have always depended on complex linkages with their immediate surroundings, as well as with more distant places, the speed, reach, and impact of these interconnections have become truly global, and will continue to be so. Understanding the processes and consequences of accelerating urbanization therefore requires tracing the web of connections and interactions that link people, places, and processes together. These linkages, which span environmental, cultural, social, economic, and political realms, mean that, for example, urbanization in one location affects demand for resources or waste disposal in another.

The geographical sciences have a long tradition of examining where, within urban areas, various kinds of people live, of investigating the processes that help to create such patterns, and of assessing the implications of residential patterning for variation in access to various opportunities such as jobs, medical care, or recreation. Since the 1960s, for example, studies have documented the ways in which urban settlements are distinguished by segregation along the lines of stage in the life course (e.g., singles, couples without children, families with children, and so on), socioeconomic status, and race and ethnicity. The spatial patterning of these dimensions is different in different regions of the world (Abu-Lughod, 1969), but in every place, the patterns of where people live within cities are the outcome of a mix of public policies and household preferences.

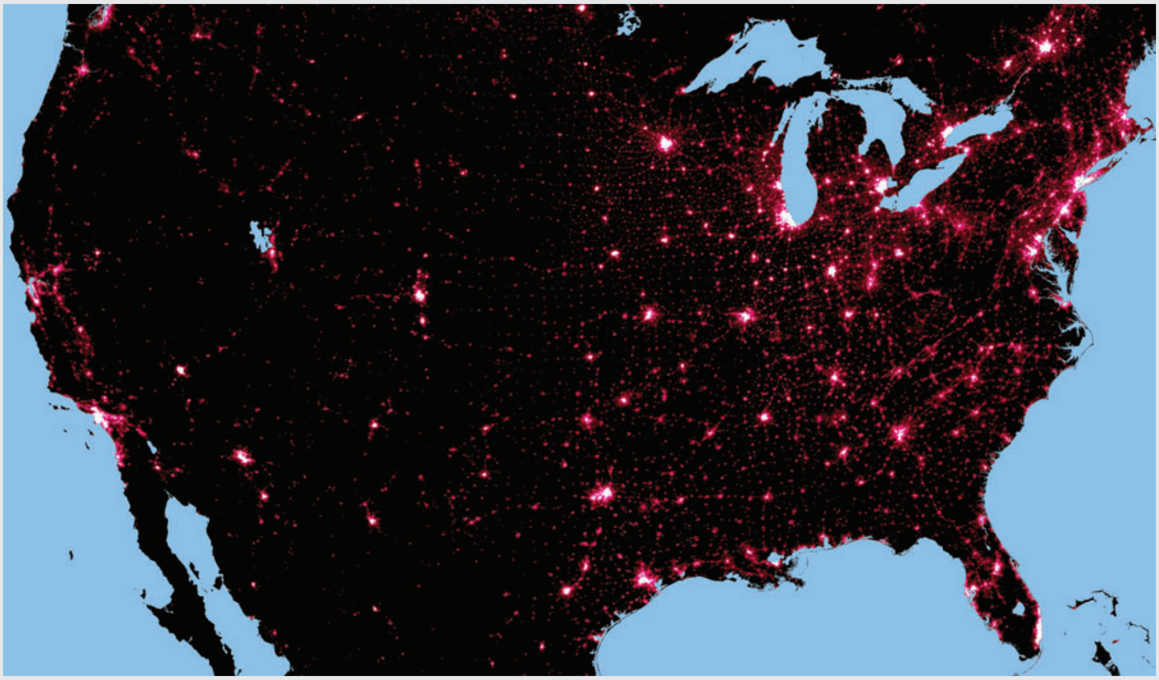
Modern geographical approaches and methods are generating insights into urban land-use patterns, from intracity to regional and global scales. The routine collection of imagery for most of Earth's land areas by satellites provides an invaluable historical record covering more than three decades. This revolutionary development makes it possible to monitor human modification and urbanization of Earth's surface across a range of spatial resolutions, from <1 m to the global scale (Sawaya et al., 2003; Zhang et al., 2004). Satellites such as Terra, Aqua, Landsat, and Tropical Rainfall Measuring Mission all provide data on the urban environment (Box 4.1).

The growing inventory of geographically indexed data makes it possible to combine satellite images with census and other information to develop analytically useful maps that show the distribution of human population around the world. For example, the Global Rural-Urban Mapping Project[4] has generated a globally consistent and spatially explicit dataset of urban population distribution. Furthermore, advances in the development of analytical methods for geovisualization, geosimulation, and spatially explicit process models have simulated urban growth (Torrens, 2006); shown the linkages between places and scales over time (Kwan,

[4]See sedac.ciesin.columbia.edu/gpw (accessed January 20, 2010).

BOX 4.1
Remote Sensing Applications Related to Human Settlements

The longest continuous observations of Earth are available through the Landsat Program, which has remotely monitored urban areas and urban growth since 1972. From the rate and magnitude of urban expansion, to population density and the global distribution of nighttime lights, satellite data have provided baseline information about the characteristics and geographical distribution of human settlements around the world. The long temporal record of satellite data is producing a clearer picture of the evolution of urban form (Herold et al., 2003; Seto and Fragkias, 2005), the impact of cities on prime agricultural land (Seto et al., 2000; Imhoff et al., 2004a), and the footprint of urban areas on local and global climate (Voogt and Oke, 2003; Jin et al., 2005; Shepherd, 2005). Data from the Moderate Resolution Imaging Spectroradiometer (MODIS) provide daily global coverage at 500-m to 1-km spatial resolution on urban characteristics such as land cover, surface albedo, aerosols, and land surface "skin" temperature (Engel-Cox et al., 2004; Zhou et al., 2004). Since 1992, the Defense Meteorological Satellite Program, Operational Linescan System (DMSP/OLS) has recorded low levels of visible and near-infrared radiance at night, making it possible to detect lights from cities, towns, and industrial sites (see Figure) (Small et al., 2005; Amaral et al., 2006). Below are examples of urban applications using satellite remote sensing data.



Nighttime lights in North America. SOURCE: National Atlas online database. Available at www.nationalatlas.gov/atlasftp.html#nitelti (accessed January 20, 2010).

2000); and provided new visual representations of data for hypothesis generation (Carr et al., 2005).

As discussed in the introduction to this report, a hallmark of the geographical perspective is the recognition that human–environment interactions and responses to changed environments are "place-based," meaning that they depend in part on particular circumstances and characteristics that coalesce in places. Especially important to a place-based analysis is the effort to understand how linkages between places shape the characteristics of settlements. Contemporary urban settlements in coastal China, for example, must be understood in the context of flows of people from villages in the countryside, flows of capital from the United States and elsewhere, and flows of raw materials and finished products that sustain manufacturing in these coastal cities (see Chapter 5). At the intraurban scale, point location data from cell phones can be aggregated at various scales to map the pattern and intensity of urban activities throughout the day, with enormous

Satellite	Spatial Resolution	Repeat Cycle	Sample Urban Applications
Landsat	15-60 m	18 days	Urban morphology (Herold et al., 2003; Seto and Fragkias, 2005); urban growth and agricultural land loss (Seto et al., 2000)
MODIS	250 m to 1 km	16 days	Urban air quality (Engel-Cox et al., 2004); urban area mapping (Doll et al., 2001; Schneider et al., 2003); footprint of urban climates on vegetation phenology (Zhang et al., 2004)
ASTER	15-30 m	16 days	Urban land cover (Netzband and Stefanov, 2004)
MISR	250-275 m	16 days	Aerosol optical thickness (Jiang et al., 2007); urban land cover (Doll et al., 2001)
AVHRR	1.1 km	9 days	Urban heat island effect (Gallo et al., 1993); urban surface temperatures (Dousset and Gourmelon, 2003)
SPOT	2.5-20 m	26 days	Urban land cover (Dousset and Gourmelon, 2003); urban detection (Baraldi and Parmiggiani, 1990)
IKONOS	0.8-4 m	3 to 5 days off-nadir, 144 days true-nadir	Urban features detection (Weydahl et al., 2005); urban road detection (Haverkamp, 2002)
SAR	10-100 m	24 days	Urban features detection (Weydahl et al., 2005); human settlement detection, population estimation, and urban land-use pattern (Henderson and Zong-Guo, 1997); urban road detection (Tupin et al., 2002)
DMSP/OLS	0.56-2.7 km	Twice daily	Population estimates (Amaral et al., 2006); urban extent (Small et al., 2005); urban energy consumption (Elvidge et al., 1997; see also Figure.

NOTES: ASTER = Advanced Spaceborne Thermal Emission and Reflection Radiometer; AVHRR = Advanced Very High Resolution Radiometer; DMSP/OLS = Defense Meteorological Satellite Program, Operational Linescan System; MISR = Multi-angle Imaging SpectroRadiometer; MODIS = Moderate Resolution Imaging Spectroradiometer; SAR = synthetic aperture radar; SPOT = Satellite Pour l'Observation de la Terre;

potential for urban and transportation planning (Ratti et al., 2006).

RESEARCH SUBQUESTIONS

What forms of urbanization are most environmentally sustainable?

Although forecasts suggest that most population growth will occur in urban areas, much less is known about which urban forms have fewer negative environmental consequences. From the design of local neighborhoods and the layout of a city, to the regional configuration of city clusters and the global geographical distribution of urban areas, how and where urban areas develop affects resource use, biodiversity, carbon emissions, and ultimately environmental sustainability. Although it is well recognized that denser, more compact settlements reduce urban growth and the physical footprint of cities, the environmental and social trade-

offs between certain shapes and sizes of cities and among distributions of cities across different ecosystems and geographical locations remain poorly understood. Cities represent the most human-dominated landscapes on Earth, but what are the consequences of different paths of urban development? What urban forms minimize resource use such as water, energy, and building materials? What are the consequences for ecosystem services, habitat fragmentation, or biodiversity of clustered urban development vs. noncontiguous metropolitan regions? What are the environmental trade-offs of 3 billion new urban dwellers being housed in megacities such as Seoul and Shanghai vs. smaller urban centers such as Chonju and Harbin?

Urban areas and urban expansion are prime causes of habitat fragmentation, habitat loss, and species extinction (McKinney, 2002). Worldwide, the transformation of landscapes for urban development has driven plant extinctions (Hahs et al., 2009). In the United States, urbanization affects more species than does any other human activity (Czech et al., 2000). The wildland-urban interface, where developed urban areas meet undeveloped wildland, is a focal zone for habitat fragmentation, the introduction of exotic species, and loss of biodiversity (Radeloff et al., 2005).

Not only do cities transform landscapes, but also urban form and urban densities affect resource use. Extensive low-density suburbanization in the United States has contributed to the growth in total vehicle miles traveled (see Chapter 7, Figure 7.1) and reduced nonmotorized travel by transit, bicycle, or foot. Extensive urban development also leads to the conversion of productive agricultural land and environmentally important ecosystems. Given increasing urbanization, which pathways of urban development will reduce the demand for energy and allow for more ecosystem services? It has long been suspected that urban land development patterns such as the density of employment and population, diversity of mixed uses, and the design of neighborhoods and streets affect the demand for travel and energy use (Cervero and Kockelman, 1997). More compact development through higher residential and employment densities can reduce energy consumption and carbon emissions. However, the energy and emissions savings are likely to be small in the short term, because the benefits of land-use changes and the reversal of current development patterns will take decades to be realized. Furthermore, the life span of the built environment and the cumulative effects of land-use change results in an increase in the cumulative savings in energy and emissions (NRC, 2009).

In the next 40 years, patterns and rates of urbanization will vary by region and within regions. The ways in which these settlements develop will affect lifestyles, landforms, and livelihoods. For example, there is growing evidence that low-density urban development is positively correlated with automobile dependence, which in turn affects walkability, physical activity, and obesity (Ewing et al., 2006; Frank et al., 2006). An epidemiological study of more than 1,500 research papers on the relationship between the built environment and obesity found that 84 percent of the studies reported a positive association between low-density urbanization and obesity (Papas et al., 2007). By definition, urban expansion transforms land cover, but where urban growth occurs also affects local ecosystem processes. The growth of Phoenix, Arizona, for example, has dramatically altered the Indian Bend Wash watershed through restructuring stream channels and creating artificial water lakes in the city (Roach et al., 2008; see also Chapter 3).

Worldwide, the fastest growing cities will be in Africa and Asia, and many of these fast-growing cities of tomorrow are just small towns today. There is, therefore, significant opportunity to direct the form of urban development and for science to help shape policies that can lead toward more sustainable and less environmentally and socially disruptive cities. An important part of the science needed to support such policies is the incorporation of uncertainty into models and scenarios of urban development.

A key question is which urban forms are more sustainable under different environmental and sociocultural conditions. For example, cellular automata research has generated insight into the evolution of urban land-use patterns and dynamics (White and Engelen, 1993; Batty, 1997; Clarke et al., 1997). Coupling cellular automata models and agent-based models can simulate decision making and represent complex spatial interactions of stakeholders (Parker et al., 2004). Spatially explicit multiscale models of urban expansion and land-use change can provide environmental indicators such as carbon sequestration, habitat fragmentation, and biodiversity (Alberti and Waddell, 2000; Theobald, 2005; Verburg et al., 2008). A growing

research community is coupling historical approaches with modern geographical methods to reconstruct the spatial history and urban ecology of cities (e.g., the Mannahatta Project[5] and the Spatial History Project[6]). For example, a spatial historical analysis that compares the growth of Bangalore, India, with Silicon Valley in the United States shows that roads drive expansive urban development and farmland loss in Silicon Valley, but not in Bangalore (Reilly et al., 2009). Satellite image analysis can provide information on what configurations, forms, and size of human settlements have the least ecological impact. For example, nighttime city lights derived from satellite data have been used to assess the effect of urban development on soil resources (Imhoff et al., 1997) and net primary productivity (Milesi et al., 2003). Satellite data have also been used to map the effect of urban expansion on long-term ecological changes (Ellis et al, 2006), agricultural land loss (Seto et al., 2000), and forest fragmentation (Wang and Moskovits, 2001). Geographical data and geographical analysis can also help quantify the spatial structure of urban development (Seto and Fragkias, 2005; Keys et al., 2007) and evaluate the effects of urban form on water use (Jantz et al., 2004; Guhathakurta and Gober, 2007), energy demand (Ewing and Rong, 2008), and air quality (Stone et al., 2007).

How can urban areas adapt to and become more resilient to global environmental change?

Human-induced alterations and transformations of Earth drive environmental changes that are global in scale (Vitousek, 1992). At the same time, global environmental change will have a wide spectrum of effects on urban areas. Climate-related effects on urban areas include increases in temperature, heat stress, sea-level rise, storm surges, threats to building stock, energy and transportation infrastructure, and urban flooding, drainage, and landslides (NRC, 2008c). The increase in the frequency and magnitude of extreme events such as wind, snow, ice storms, hurricanes, and heat waves will threaten building stock, energy and transportation infrastructure, and ultimately the well-being of urban populations. Studies of the 1995 and 1999 Chicago heat waves conclude that housing infrastructure, in particular active cooling systems, was the strongest protective factor against heat-related death (Naughton et al., 2002). Existing transportation infrastructure may not have been designed to withstand extreme events associated with climate change. The vulnerability of transportation and energy infrastructure will depend on the rate of warming, the types of extreme events that occur, and new design standards for buildings and infrastructure. How can urban areas adapt to the suite of global environmental changes?

The ability of urban areas to cope with changing global environmental circumstances depends on geographic location in relation to a range of physical and human circumstances, the capacity of local political and economic institutions to deal with disruption, and the organization and physical character of the built environment. Different types of global environmental changes (e.g., sea-level rise, extreme heat, or prolonged drought) can also affect urban adaptive capacity in variable ways. Around the world, evidence is growing that there is an increase in extreme weather and climate events (Alexander et al., 2006). In North America, droughts are becoming more severe, heavy precipitation events are more frequent and intense, and severe storms are increasing in power and frequency (CCSP, 2008). These intense weather and climate events could pose major threats to urban systems and disrupt urban activities. Furthermore, depending on the nature of extreme events, they could exacerbate existing local environmental conditions—reducing water quality, threatening sanitation and public health, worsening local air quality, and intensifying the urban heat island effect.

However, climate change is not the only type of global environmental change to which urban areas will need to adapt. Changes in the hydrological cycle and water availability will constrain future urban growth and require water quantity management across multiple jurisdictions of metropolitan areas (Holway, 2009). Cities near rivers and in delta systems will be particularly threatened by flooding and landslides. Thirteen percent of the world's urban population lives in low-elevation coastal zones, defined as coastal regions less than 10 m above sea level (McGranahan et al., 2007). These coastal communities will be particularly vulnerable to sea-level rise and storm surges.

More comprehensive knowledge and understanding of global environmental change and its consequences

[5]See www.mannahattaproject.org (accessed January 20, 2010).
[6]See spatialhistory.stanford.edu (accessed January 20, 2010).

for urban areas will be needed if local decision makers, communities, and individuals are to prepare, cope, and adapt to these changes (Sánchez-Rodríguez et al., 2005). Adaptation research has focused on two issues (Burton et al., 2002): (1) How can adaptation reduce the impacts of climate change, and (2) what types of adaptation policies are needed? More than 20 cities around the world—particularly in Europe and North America—are in the process of developing local climate change adaptation and action plans. For example, the Chicago Climate Action Plan outlines strategies for mitigating climate and actions to prepare for climate change adaptation. Similarly, the London Climate Change Adaptation Strategy identifies key climate risks and prioritizes adaptation strategies. However, recent research shows that local adaptation strategies may conflict with mitigation efforts. One community on the north coast of Australia's New South Wales has a policy that requires new residential developments to maintain vegetative cover and preserve wildlife habitat for the local koala population. To achieve these goals, however, the developments must be low density and car dependent, which in turn increases driving and energy consumption. Furthermore, siting homes in natural vegetation also increases exposure to other climate change risks such as fire (Hamin and Gurran, 2009).

Advances in spatially explicit modeling and geographical simulation can deepen understandings of how cities can be more resilient to global environment change. A first step in evaluating possible adaptation and mitigation strategies is knowledge about where cities are growing and their vulnerabilities to global change (Chapter 3). In many African countries, urban population statistics are out of date or lacking, making the task of mapping the location and growth of urban settlements particularly challenging (Cohen, 2004). In these regions, much of the housing is informal (Satterthwaite, 2007). Because censuses are absent, infrequent, or unreliable in many regions and because informal settlements often lack official recognition, many of these settlements become "invisible towns" (Stickler, 1990), highlighting the need for studies using modern geographical tools to map and understand settlement locations and growth patterns.

There is a similar need to understand the patterns of urbanization in Asia, where 16 of the world's 27 largest urban agglomerations will be located by 2050. Accurate and timely mapping and forecasting of urban settlements will be important for a range of applications, including anticipating infrastructure needs; planning for emergency response systems (Kwan and Lee, 2005); identifying regions and communities at risk from storm surges, sea-level rise, and natural hazards; and mapping urban growth and loss of natural and agricultural land (Hasse and Lathrop, 2003). Cellular automata models that were initially developed by Von Neumann (1966) are now used widely to predict urban growth in a range of cities around the world, including San Francisco (Clarke et al., 1997); Beijing, China (Chen et al., 2002); Chillán, Chile (Henríquez et al., 2005); and Lagos, Nigeria (Barredo and Dermicheli, 2003). Other methods are being developed that do not have large data requirements and will be especially applicable in developing country contexts (Fragkias and Seto, 2007). Understanding where and how intra- and interurban settlements are changing, or are likely to change, provides fundamental information and insights to urban planners and policy makers. Innovations in the geographical and computer sciences—especially online mapping and real-time geographic information systems (GIS)—are bringing together different types of spatial data from multiple sources (from governments to individuals) to increase their timeliness and utility for societal benefit. Rather than using static risk or hazard maps that suggest that vulnerability is unchanging, dynamic GIS with real-time information and real-time computing can provide up-to-date information on the distribution of vulnerability across landscapes and can differentiate risk among different communities within cities (Bankoff et al., 2004). For example, as in other parts of the world, most of the largest Asian cities are located on a river bank, in a delta, or along the coast (UN Habitat, 2008), making them particularly vulnerable to climate change, sea-level rise, flooding, and other extreme events. In the case of the 2004 Asian tsunami, GIS-based vulnerability models coupled with demographic methods of tsunami-displaced populations were used to quantify mortality estimates, methods that could also be used in the early stages of disaster relief (Doocy et al., 2007).

The uncertainties associated with climate change, as well as with the formation of human settlements, pose challenges for analysts and policy makers alike. Advances in geovisualization and geosimulation can help inform adaptation strategies under different

TABLE 4.1 Various Pathways Through Which Urbanization Affects the Climate System

	Urban Land Cover	Urban Aerosols	Anthropogenic Greenhouse Gas Emissions
Urban heat island (UHI) and mean surface temperature record	Surface energy budget	Insolation, direct aerosol effect	Radiative warming and feedbacks
Wind flow and turbulence	Surface energy budget, urban morphological parameters, mechanical turbulence, bifurcated flow	Direct and indirect aerosol effects and related dynamic/thermodynamic response	Radiative warming and feedbacks
Clouds and precipitation	Surface energy budget, UHI destabilization, UHI mesocirculations, UHI-induced convergence zones	Aerosol indirect effects on cloud-precipitation microphysics, insolation effects	Radiative warming and feedbacks
Land surface hydrology	Surface runoff, reduced infiltration, less evapotranspiration	Aerosol indirect effects on cloud-microphysical and precipitation processes	Radiative warming and feedbacks
Carbon cycle	Replacement of high net primary productivity land with impervious surface	Black carbon aerosols	Radiative warming and feedbacks, fluxes of carbon dioxide
Nitrogen cycle	Combustion, fertilization, sewage release, and runoff	Acid rain, nitrates	Radiative warming and feedback, NO_x emissions

SOURCE: Seto and Shepherd (2009).

urbanization and global change scenarios. For example, the WaterSim Project[7] simulates water supply and demand in a desert city. The simulation and forecast tools being developed in conjunction with this project can help cities evaluate policies to adapt to a water-constrained environment.

What are the impacts of accelerating and large-scale urbanization on local and regional climate patterns?

There is a growing scientific understanding of the relationship between urbanization and climate (Voogt and Oke, 2003; Shepherd, 2005). Urbanization alters climate through multiple pathways (Table 4.1).

Locally, the conversion of vegetated surfaces to urban areas modifies surface energy balance dynamics (Lo et al., 1997; Banta et al., 1998). Altering the exchange of heat, water, trace gases, aerosols, and momentum between the land surface and overlying atmosphere leads to the urban heat island effect, which is characterized by elevated daytime and nighttime temperatures in and near urban areas compared to non-urban or rural areas (Arnfield, 2003; Crutzen, 2004). The urban heat island effect is further affected by the interaction among building geometry, land use, and urban materials (Oke, 1973; Arnfield, 2003).

Urban areas have been shown to produce a warming trend over regional climate (Kalnay and Cai, 2003), and there is mounting evidence that urban areas also affect precipitation (Lowry, 1998; Shepherd and Jin, 2004). It has long been known that urban areas alter their regional and microclimates, resulting in an increase in rainfall downwind (Landsberg, 1970). Empirical evidence shows that in some regions, urban expansion and urban air pollution result in a decline in rainfall (Amanatidis et al., 1993; Rosenfeld, 2000; Kaufmann et al., 2007). In other places, urbanization has induced precipitation and possibly created thunderstorms, leading to significant anomalies in precipitation patterns (Figure 4.3) (Dixon and Mote, 2003). In places where it has been shown that urban areas increase rainfall, the difference can be as much as 5 percent to 25 percent (Mote et al., 2007). In addition to the quantity of rainfall, cities can also affect the timing and formation of thunderstorms and the severity of precipitation, as has been found for Tokyo (Yonetani, 1982), Beijing (Guo et al., 2006), Atlanta (Bornstein and Lin, 2000), Mexico City (Jauregui and Romales, 1996), among others. These changes imply

[7]See watersim.asu.edu/ (accessed January 20, 2010).

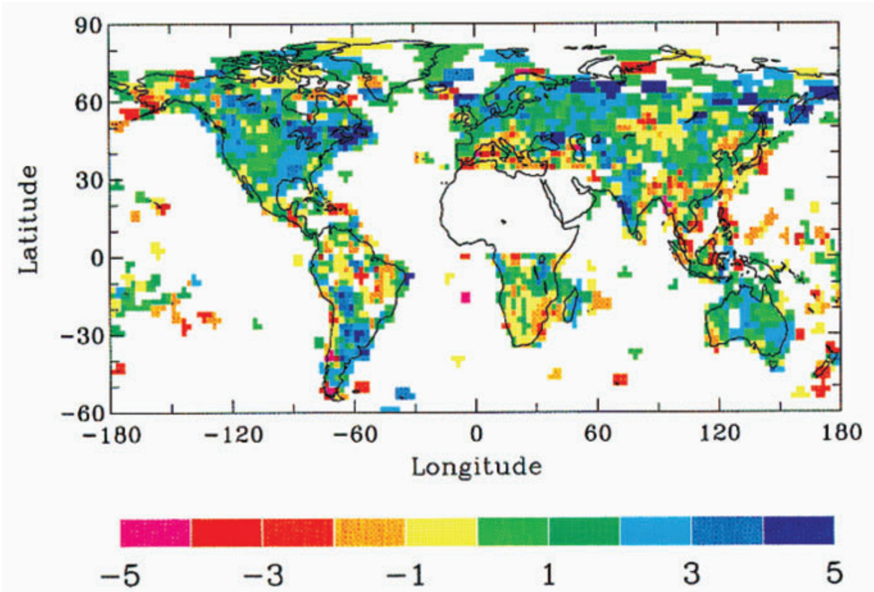


FIGURE 4.3 Annual precipitation anomalies, 1900–1988. Regions in blue show an increase in precipitation over the mean during the 1900–1988 period. Regions in red have become relatively drier during the same period. Areas without data are shown in white. SOURCE: Dai et al. (1997).

that urban land uses and urban expansion through land-cover change can affect local, regional, and global climate at diurnal, seasonal, and long-term scales (Stohlgren et al., 1998; Zhou et al., 2004).

A clearer picture is emerging that urban areas can affect climate at different scales. However, we lack a comprehensive understanding of the dynamics by which urban expansion will affect climate; nor do we understand the interactions between local-scale dynamics and regional and global patterns. We also have a fragmented picture of urban land-use patterns at a global scale. Most analyses of urban land use are based on individual case studies of city or metro regions, and there are few comparative, regional, or global studies (Seto and Shepherd, 2009). We have a good understanding of some of the ways that urban areas affect climate at several scales, but we lack comprehensive understanding, and more importantly, an understanding of how urban growth—or different forms of urban growth—will affect climate. Given the magnitude of the global urban transition of the 21st century, there is an urgent need to understand the impact of urban land-use change on precipitation and temperature, and to forecast scenarios of urban expansion and their possible impacts on precipitation changes. How will the growth of settlements affect rainfall and temperatures at local, regional, and global scales?

Continued advances in understanding the link between urban land use and regional climate will require mining a variety of data—from remote sensing of clouds, aerosols, and land to field-based meteorological data on temperature and precipitation. It will require modeling urban climates at fine spatial scales to understand the effect of building materials, street geometry, and building geometry on local temperatures (Oke, 1973, 1981), explicit treatment of urban land use in climate models (Bonan et al., 2002; Jin et al., 2005), and techniques for downscaling general circulation models (Wilby and Wigley, 1997).

SUMMARY

Urbanization in the 21st century will have far-reaching effects ranging from the local to the global. Understanding where people will live and how cities will develop in the future has implications for all aspects of human and environmental well-being discussed in this report, from the provision of food for a growing urban population to safeguarding our planet's biodiversity and ecological services. New geographical data and emerging analytical methods, combined with existing research tools and techniques will help develop a more coherent and complete understanding of the patterns, implications, and uncertainties of urbanization.

5

How Will We Sustainably Feed Everyone in the Coming Decade and Beyond?

The global population will likely peak at 8 billion to 12 billion in the latter half of this century, up from 6.7 billion in 2008 (Population Reference Bureau, 2008). When global food (and related resource) consumption will crest is unknown, because the quantity of food energy consumed globally and the amount of fossil fuel energy, water, land, and soil resources used to produce these kilocalories is only partially related to the size of the global population (Imhoff et al., 2004b). The critical challenge of sustainable food production and distribution not only depends on knowing how many people live where and how fast populations are growing, but also on the quantities and types of food consumed, the cost of food, and access to food (Bayliss-Smith, 1982; Meyer and Turner, 1992). In general, as incomes rise, people consume more meat and processed foods, demand fruits and vegetables with fewer blemishes, want fresh produce in all seasons, and import foodstuffs from increasingly distant locations (e.g., Leppman, 2005). These changing food consumption preferences are straining global food production and distribution systems, leading to growing concern that these systems will not be adequate to sustainably meet rising food demands in the coming decade (e.g., Tilman et al., 2002; von Braun, 2007).

Changing food consumption patterns interact with agricultural production systems, which are increasingly interlinked across the globe and face a dynamic set of constraints. These constraints include (1) varying abilities to balance production and consumption across regions and countries, (2) accelerating conversions of agricultural land to urban uses, (3) increasing energy-intensive food production methods in a world of shrinking fossil fuel resources, and (4) expanding use of food crops for biofuel production. According to the Food and Agricultural Organization (FAO, 2008), these forces and others (such as financial speculation) have converged to drive a steady increase in global food prices since 2000, with prices rising almost 50 percent between April 2007 and March 2008 (Figure 5.1).[1] Since the trajectory of the curve is uncertain in the years ahead, a key question for the future is whether the upward trend will continue, and to what effect. Rising food prices are creating hardships, especially among the poor in market economies, as suggested by the food riots that broke out in several West African cities and beyond in the wake of the 2008 spike in food prices.

On a global scale, per capita food production increased by 0.9 percent annually between 1980 and 2000, but this figure disguises considerable variation in production between regions, not to mention levels of access to the food being produced. Food production per capita during this period grew by 2.3 percent in Asia and 0.9 percent in Latin America, but it declined 0.01 percent in tropical Africa (Kates and Dasgupta, 2007). Data on food consumption in low-income countries are scarce, but an estimated 43 percent of people in Sub-Saharan Africa are chronically undernourished, as compared with 22 percent in South Asia and 12-16 percent in other low-income areas (Pinstrup-Andersen and Pandya-Lorch, 1999). At finer spatial scales, additional disparities emerge. Regional differ-

[1] The recent rise in food prices should be viewed against a history of even higher (real) price increases for food.

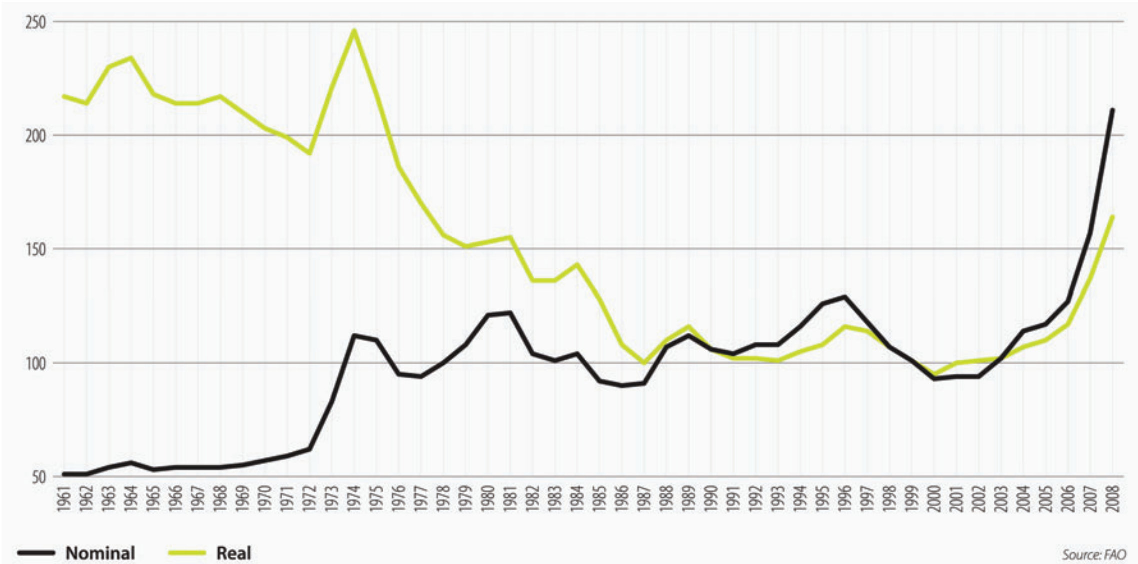


FIGURE 5.1 Extended Annual FAO Food Price Index, 1961-2008 (1998-2000 = 100). The green line traces real value, which adjusts for inflation, while the black line traces nominal value, which reflects the actual price in each year. Note the sharp rise that begins in 2006; the average growth rate over the 2000-2005 period was 1.3 percent per year, but has jumped to 15 percent since 2006. A key question for the future concerns whether the upward trend will continue, and to what effect. SOURCE: FAO (2008).

ences in food availability and consumption represent a significant societal challenge—condemning millions in some places to persistent hunger, if not death, and fostering instability. In the coming years, cultivation on prime agricultural lands will almost certainly intensify worldwide, and marginal lands will increasingly be taken out of production (Turner, 2001). This process is already beginning in the high-income countries, often in situations where critical resources (such as water from aquifers) have been depleted. Where agricultural production continues on marginal lands, it is often supported by subsidies. Intensified production relies on significant fossil fuel and chemical inputs, as well as irrigation. The overall reduction in and intensification of agricultural lands are not necessarily being repeated in lower income countries in the tropics. There, life-sustaining, yet economically marginal farming continues to expand into the forest frontier, often following roads built for timber and other extractive industries, or corporate and large-scale agriculture seeking to capture inexpensive land (Lambin and Geist, 2006). There are no clear indications that this process will cease in the near future, although it will surely vary by region.

Globally, farmland is being lost to urbanization at unprecedented rates. The expansion of cities (see Chapter 4) is converting agricultural land to nonfarm uses (Gardner, 1997; Imhoff et al., 2004a). Between 1987 and 1992, China lost more than 1 million hectares of farmland to urbanization (Seto and Kaufmann, 2003). There is growing concern that urbanization rates in the 21st century will place significant new pressure on arable land, and that the loss of farmland to urbanization will be a threat to yield and total output (Imhoff et al., 2004a). Thus, we need to better understand the links between demographic and economic circumstances on the one hand, and agricultural production and consumption on the other.

The explosive growth in industrialized or high-input agriculture raises a set of important questions. Technologically intensive agriculture uses large amounts of fossil fuel energy, water, inorganic fertilizers, and pesticides to produce large quantities of a single crop (monocultures) or to raise livestock. The mixed history of industrialized, high-input agriculture helps explain why there was much debate about how to sustainably address the 2008 global food crisis. Many of the world's most influential policy voices called for a renewed emphasis on food production, and particularly on increased yields through biotechnology and new green revolution approaches (e.g., Borlaug, 1995, 2000;

FIGURE 5.2 Smallhold farm family on break in southern Mali. The pictured field has a mix of crops (sorghum and cowpeas) and trees (shea nut or *Butyrospermum parkii*), an illustration of the polycropping strategies. SOURCE: William Moseley, used with permission.

Sachs, 2006; Annan, 2007). Others saw green revolution approaches to solving the world's food problems as flawed because of associated environmental and social consequences (Yapa, 1996; Das, 2001; Carney, 2008). Better understanding of the issues relevant to this debate is critical to addressing the challenge of how to sustainably feed a growing population.

ROLE OF THE GEOGRAPHICAL SCIENCES

Geographical scientists studying food production and consumption take an approach that is distinctive in several ways.[2] First, they examine food production and consumption as a form of human–environmental interaction, an approach distinguished by its treatment of both the social and biophysical sides of this coupled dynamic and by the use of the suite of systems that facilitate the acquisition, storage, and analysis of geographical information discussed in Part I. The interdisciplinary subfield of land-change science has been at the forefront of this effort over the past decade (Gutman et al., 2004; Lambin and Geist, 2006; Turner et al., 2007; Turner and Robbins, 2008). Studies of indigenous or traditional agricultural systems (e.g., Grossman, 1981; Richards, 1985; Bebbington, 1991; Grigg, 1995; Mortimore and Adams, 2001) have advanced understanding of farming in the tropics by, for example, documenting the know-how and techniques of smallhold farmers who often used mixed or polycropping strategies that capitalize on agroecological relationships (between crops, crops and trees, and crops and insects; Figure 5.2). These indigenous approaches, once considered backward and primitive, are now acknowledged to be more efficient from an energy input-output standpoint under most circumstances (Bayliss-Smith, 1982; Pimentel et al., 2002) and have inspired new strategies within the organic farming movement that are celebrated in such popular works as Michael Pollan's *The Omnivore's Dilemma* (2006) or Barbara Kingsolver's *Animal, Vegetable, Miracle* (2007).

[2]This same geographical approach could be applied to address sustainability questions in other resource (water, energy, mineral, biological) systems.

Geographical scientists also have contributed to debates concerning the question of whether food production is capable of keeping up with population growth. The original work of Malthus (1798/1987), and then subsequent work by neo-Malthusians (such as Ehrlich, 1968), suggested that population growth would eventually outstrip food supply. Boserup (1965) advanced an alternative proposition, largely based on historical research, suggesting that growing population density often led to the intensification of agriculture and rising output through increasing labor inputs and infrastructure investments (e.g., terracing, irrigation). The desire to test these two competing hypotheses (Malthusian and Boserupian) in the contemporary era led geographical scientists to turn to the "natural experiment" approach, exploring the relationship between population and agricultural change in many different locations.

Mortimore and Tiffen (1995) undertook an intensive study in one location—Machakos, Kenya—which showed that increasingly dense populations were able to produce more and more food. In contrast, Turner and colleagues (1993) examined several cases across Africa with differing outcomes, as did Turner and Shajaat Ali (1996) in several villages across Bangladesh, or Laney (2002) in Madagascar. These studies point to the conditions under which increasing population can lead to agricultural intensification and increased output, as opposed to declining productivity and environmental degradation.

Second, geographical scientists use spatial analysis to study food production and consumption. They are attuned to the ways in which food production and consumption systems are often connected across places and regions via processes operating at different spatial scales. A study by von Thünen (1826/1966) of the 19th-century spatial pattern of food production outside German cities showed that the type of crop a farmer (wanting to maximize his profit) would choose to cultivate at any location, and the intensity with which it would be cultivated, was a function of the distance of the location from the city, the cost of transportation, and the perishability of the crop. Newer approaches that are attuned to these relationships have provided insight into the changing character of agricultural systems, hunger and famine, and consumption. Geographic information systems can be used to organize and synthesize data on climate, hydrology, soils, and crop yield, which can facilitate the management of food production in water-scarce regions. Remote sensing can be useful in planning for arable land extension and detecting the incipient stages of water scarcity and its impacts on crop yield. Looking forward, such techniques can help pave the way to the development of a new and integrative science of dryland management (Reynolds et al., 2008), which can be of use to policy makers, resource managers, and farmers facing the challenge of water scarcity.

Third, the work of geographical scientists has also provoked researchers to think more broadly about food supply and agricultural questions by bringing scale (and the connections between regions and places) into the analysis. The historical and comparative work of Carney (2001), for example, has shown how the agricultural know-how of West African slaves—not Europeans—was largely responsible for the development of a rice export economy in the American Southeast in the 17th and 18th centuries. Work of this sort demonstrates that seemingly local questions concerning agricultural change, or the ability of a population to feed itself, need to be set within a much broader web of relationships in space and time. A multiscalar approach is also vital to understanding contemporary and future food challenges. Diana Liverman, for example, has demonstrated how we can better understand the impact of global climate change and globalization on small farmers in Mexico (see Box 5.1).

The impacts of the steep rise in food prices during spring and summer 2008 hit hardest in urban West Africa. Many pointed to declining per capita food production in Africa as the source of the problem (Sachs, 2006; Annan, 2007). Others saw the connections between different regional food markets as being important as well (Moseley et al., 2010). As of the late 1970s, those living in urban West Africa still ate largely locally or regionally produced grains. By 2008 they were purchasing rice from Thailand or Malaysia, having developed a taste over several years for this relatively cheap import (Pearson, 1981; Carney, 2008; Seck, 2008). A regional food problem developed when these imported grains skyrocketed in price. This problem was caused by a number of factors operating at multiple scales and in several locations across the world, including shifts in the global market, agricultural practices,

BOX 5.1
Farmers Adapting to Changing Climate and Political Economy in Mexico

Diana Liverman exemplifies several aspects of what geographical scientists have to offer to agricultural questions. Trained in both human and physical geography, Liverman has a long-standing interest in the human dimensions of global change (Liverman, 1998, 1999, 2008). Born in Ghana, and educated in England, Canada, and the United States, she was interested initially in the potential and limitations of predicting climate impacts using both crop simulation models and the first generation of global models that allowed for the assessment of climate change impacts. However, as it became clear to her that the scientific community's knowledge of climate impacts in the developing world was insufficient for modeling, and that some of the most interesting questions were about how people and places became vulnerable to climate change, much of her work came to focus on the vulnerability to drought of farmers in the drylands of Mexico. By studying small and large farmers in the Sonora and Puebla states of Mexico, Liverman was able to quantify the impacts of land tenure and technology on vulnerability to drought. Here she found that those with access to irrigation have lower drought-related crop losses, and farmers on communally held ejido land are more at risk from drought than large private farms (Liverman, 1990,1999). Of course technology and land tenure are correlated in Mexico, because the large private farms are more likely to have irrigation than communal (or ejido) land. Furthermore, private landowners are more likely to have access to higher quality land, which has a bearing on crop losses during low-rainfall years. Liverman's work in this area was important because it showed that patterns of crop loss could depart from levels of rainfall because of differences in agricultural vulnerability between households. She also has considered the influence of politics and economics on farming and ranching decisions in the face of changing climatic conditions (Vasquez-Leon and Liverman, 2004; Liverman and Vilas, 2006).

and urbanization. Research into the kinds of questions outlined below could enhance our understanding of what happened in 2008 and related food challenges.

RESEARCH SUBQUESTIONS

Which farming systems will be most and least able to cope with climate change?

One of the great challenges of the 21st century is to meet the growing demand for food even as climate change is affecting agricultural and farming systems (Easterling, 2007). Climate models are consistent in predicting drier conditions over much of the subtropics and adjacent dryland areas by the mid to late 21st century (Wang, 2005; Seager et al., 2007; Bates et al., 2008). The drying is driven by increased temperatures and resulting evaporation, and by decreased precipitation. Climate models have been particularly consistent in projecting drier soil conditions in southwestern North America to Central America, the circum-Mediterranean and Middle East, Australia, and southern Africa (Wang, 2005). Although climate model results are coalescing on a consistent picture of drier conditions in the subtropics and adjacent dryland regions in both the Northern and Southern Hemispheres, the degree of increased aridity may also be influenced by changes in ocean circulation that are still poorly resolved in current climate models (Vecchi et al., 2008). Looking forward, spatially explicit climate research, extending from global to regional climate models, could help refine projections of which farming systems will be most and least able to cope with climate change by predicting where aridity will increase.

Understanding which farming systems will be most affected by environmental change also requires careful assessment of the location and fragility of current systems. We know that dryland farming areas, where some 2 billion people currently live, are the most sensitive to changes in precipitation (Oki and Kanae, 2006). These sensitive areas are concentrated in the subtropics and adjacent regions—particularly Sub-Saharan Africa (Sullivan et al., 2003)—but more research is needed to understand how they would be influenced by longer term drying trends. As noted by Kates (2000), some low-income countries may be able and inclined to address climate change and protect agricultural productions via dams and irrigation schemes, yet these schemes often have serious consequences for the poorest farmers who are likely to lose land or have limited access to the water they provide (Gellert and Lynch, 2003). Livelihood systems (broader systems encompassing farming and nonfarming activities) developed in dryland regions with highly variable rainfall tend to exhibit the strategies of risk-averse smallhold farmers, such as diverse cropping strategies, grain storage, the deliberate straddling of multiple microenvironments, and the seasonal migration of certain family members (Mortimore, 1989; Davies, 1996; Moseley, 2001).

A key research question is whether these systems can accommodate more drastic levels of change. Furthermore, many systems are now more vulnerable to environmental variability because they have changed in order to meet regional and global market demands for certain products as a result of increased globalization, leading to a potential double exposure to market and climate change (O'Brien and Leichenko, 2003). As such, geographical assessments of vulnerability of the type described in Chapter 3 will also be important to the effort to understand the adaptability of different farming systems.

How do changing consumption patterns, regulations, and costs in one place affect farming systems, land use, and food security in other places?

Food networks are interconnected, spanning world regions, as well as urban and rural domains. The past two decades have been dominated by continued protection of agricultural producers in high-income countries and market-oriented reforms in low-income states. The persistence of protection for farmers in the high-income countries reflects the power of the farm lobby and associated input producers (Watts, 2000). Increasing free trade in food crops has often led to the demise of smallhold producers in low-income countries, as well as the consolidation of farms (Fitting, 2006). There is also evidence that certain World Trade Organization, FAO, and World Bank policies have undermined local control and human rights in some places (Pogge, 2008). Research from a geographical science perspective, taking into account the linkages between places and policies, can yield a better understanding of the implications of these changes for food security and farming systems, including who is affected by these practices, where they are located, and how they are affected. Similarly, a better understanding of the food security implications of more robust local and national food systems is critical.

We also need to understand the spatial and functional impacts of land-use changes brought about by local and regional factors. Blaikie, who undertook groundbreaking research on the topic, showed how land degradation and soil erosion in Nepal was not just a local issue, but a phenomenon influenced by broader social and economic processes (Blaikie, 1985; Blaikie and Brookfield, 1987). This research area needs to be continually updated as the nature of the global food economy changes. As discussed previously, urban expansion has eroded the availability of good agricultural land in many places, but the impacts of this process on food production are poorly understood. National and subnational geographically explicit agricultural data (including yield trends) could be combined with satellite imagery to provide assessments of the quality and availability of farmland. Scenarios of urban expansion can be coupled with maps of cultivated land to identify hotspots of farmland threatened by urban expansion. Urbanization in one area may also be affected by distant points of consumption, and can affect agricultural systems in other parts of the globe. For example, Asian urbanization and industrialization changes local diets and influences the demand for food and raw materials produced in places as far away as Africa (Muldavin, 2007). South Korea recently acquired plantations in Madagascar to produce food for its people (Walt, 2008).

Energy costs are an important factor in food production systems. Bayliss-Smith (1982) was one of the first scientists to examine food production systems around the world from an energy efficiency standpoint. Although industrialized agriculture produces higher yields, it is less efficient in terms of the amount of energy inputs required to produce a unit of output. In the United States it takes about 2.2 kcal of fossil fuel energy, on average, to produce 1 kcal of plant protein (Pimentel et al., 2002). Furthermore, food producers increasingly ship their products long distances to reach intended customers. According to the U.S. Department of Agriculture (Regmi, 2001), the United States imported 11.6 percent of its vegetables and 38.9 percent of its fruit in 2001 (up from 4.1 percent and 20.8 percent in 1970). The emergence of a more globalized food system—a phenomenon driven by cheap fossil fuel–based transportation for nearly two decades (1985 to 2005)—may change, however, if transportation costs climb (Rohter, 2008). The notion of virtual water and energy in food exports and imports (i.e., the amount of water or energy expended to produce an agricultural crop) is also important for understanding indirect exchange of these resources associated with agricultural trade (Allen, 2000; Turton, 2000).

Both spatial and functional interconnections will affect the evolving global food picture. Many of the

future research questions in this vein are inherently geographical, and given increasing food prices, growing landlessness, urbanization, and rising (food-price related) civil unrest, research at the human–environment interface will become more pressing.

Where are genetically modified crops (GMCs) being most rapidly adopted and with what consequences for food supplies and rural livelihoods?

Even though multiple factors contributed to the food crisis of 2008 (including use of grain crops for ethanol production, financial speculation, increasing meat consumption in the low-income states, rising energy prices, and a growing population), many of the proposals for avoiding another food crisis focus on technological fixes, particularly the expanded use of GMCs. GMCs often elicit a bifurcated response—they are either cast as beneficial to both the environment and food production (Federoff and Brown, 2004) or criticized for their corporate origin and control, and their potential negative effects on agriculture.[3] Evaluating these different claims requires geographically grounded empirical studies at multiple scales (household, village, region) in regions where GMCs have been introduced.

While the green revolution approach (involving the use of hybrid seeds, irrigation, fertilizers, and pesticides in low-income countries) increased yields, it also created a host of environmental and social problems. Proponents of GMCs argue that these crops not only increase yields, but also they avoid many of the environmental problems associated with the green revolution approach, including pesticide and fertilizer runoff. Critics of GMCs are concerned about corporate control of seeds, the access of the poor to GMC packages, and genetic contamination of wild species (McAfee, 2003; Roff, 2008; Sitko, 2008). Early studies in South Africa indicate that genetically modified cotton was initially adopted with great success, but that later most farmers were abandoning the crop because agricultural extension services were inadequate and net profits were less than those obtained with conventional cotton (Gouse et al., 2008). In 2008, Burkina Faso became the second African state to openly adopt GMCs, essentially the same genetically modified cotton that failed in South Africa (Dowd, 2008).

Charting the social and environmental consequences of such experiments in coming years could reveal the positive and negative impacts of GMC adoption in different regions. Studies integrating the physical and human dimensions are particularly needed, as one of the critical underresearched issues concerns the changing biogeography of genetic contamination (Parker and Markwith, 2007). Finally, the GMC approach needs to be compared to other agricultural methods, such as the system of rice intensification, which was initially developed in Madagascar and is now being tested in Asia and West Africa (Broad, 2008).

SUMMARY

Sustainably feeding Earth's population over the coming decade and beyond requires better understanding of how food systems interact with environmental change, how they are connected across regions, and how they are influenced by changing economic, political, and technological circumstances. The geographical sciences' analysis of food production and consumption, when coupled with recent conceptual and methodological advances, can provide new insights into this critically important research arena.

[3]The top GMCs in the world in 2006 by area were soybeans, maize, cotton, and canola (with soybeans accounting for over half of this area). The world's leading producers of GMCs are the United States, Argentina, Brazil, Canada, India, and China (with the United States having nearly three times as much hectarage as Argentina in such crops). Other significant producers are Paraguay, South Africa, Uruguay, and Australia (GMO Compass, 2007).

6

How Does Where People Live Affect Their Health?

Health has always been a fundamental social concern, but apprehension over health issues has escalated in recent years in the wake of extensive media coverage of disease outbreaks, the rapid spread of infectious diseases around the world, growing evidence of the health impacts of exposure to the by-products of industrialization, and anxieties about the availability and affordability of health care. Because environmental factors play a fundamental role in shaping human health, locational issues are of central importance to addressing health questions. A variety of place-based influences affect health, including physical circumstances (e.g. altitude, temperature regimes, and pollutants), social context (e.g., social networks, access to care, perception of risk behaviors), and economic conditions (e.g., quality of nutrition, access to health insurance). Because locational influences are myriad and constantly shifting, and because people themselves are moving around at unprecedented rates (Chapter 7), understanding the health impacts of where people live is one of the most challenging, yet important, contemporary geographical problems.

The influence of location on health is clear even at the global scale. The best way to reduce the worldwide burden of disease may be to provide individuals with ready access to clean water, adequate nutrition, and rudimentary sanitation, yet the availability of these "big three" basic needs differs greatly from place to place. People's access to immunization is perhaps the next most important variable in the health picture, yet access to immunization often depends on social circumstances and the distribution of health care facilities.

Much has been learned in the past about geographical influences on health through mapping the spread of diseases, access to care, and the treatment and prevention of illness. Coming more fully to terms with the impacts of location on human health, however, requires documenting, modeling, and predicting human health outcomes at individual- to population-level scales, while accounting for

- Human mobility (e.g., daily, weekly, seasonal, life course),
- Socioeconomic circumstance (e.g., income status, age, education, gender),
- Behavioral risk factors (e.g., smoking, drinking, drugs, diet),
- Changing environment (e.g., climate change, industrial development, urban expansion),
- Time course of disease (e.g., cancer latency, induction period),
- Genetics (e.g., determinants of predisposition to disease).

Addressing some of the major health challenges of the 21st century requires developing increasingly sophisticated theories, methods, visualizations, and tools that can help account for the intersecting impacts of these six variables in different locations (Figure 6.1).

The global resurgence of vector-borne diseases such as malaria, dengue fever, yellow fever, and Lyme disease (Gubler, 1998) highlights the need to enhance understanding of the geographical dimensions of disease occurrence and spread. Malaria alone kills an

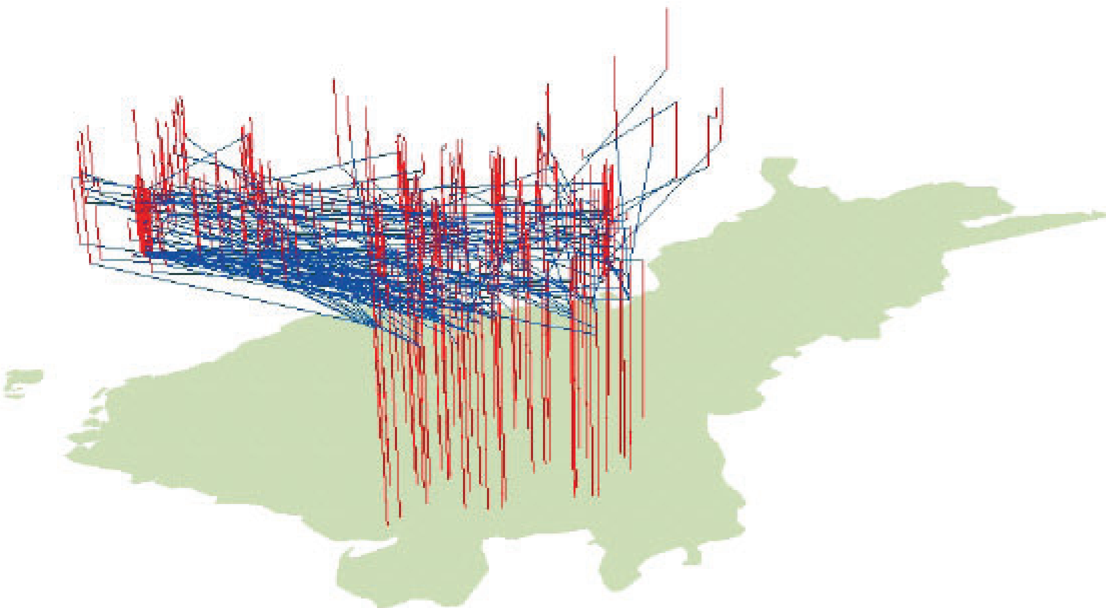


FIGURE 6.1 A three-dimensional geographical visualization of the residential mobility of 1,000 cases of amyotrophic lateral sclerosis (ALS) in southeastern Finland, distinguishing movers (blue) from nonmovers (red). The vertical lines represent periods of stability and the blue lines link the origins and destinations of the moves. Sabel et al. (2003) identified a birthplace cluster of the disease in southeast Finland—the first example of a significant ALS cluster being identified worldwide. This part of Finland has suffered from significant industrial pollution, and heavy metals are present in the environment. To determine whether these heavy metals may be implicated in the etiology of ALS, Sabel et al. (2009) used the detailed migration histories of the cases and controls to explore differences between movers and nonmovers. The results demonstrated that moving away from the area seems to be protective, meaning that the environment has a role to play in the disease etiology. SOURCE: Unpublished figure courtesy of Paul Boyle.

estimated 700,000 to 2.7 million people each year (Patz and Olson, 2006). The increasing movement of people and products is raising the specter of the spread of one of the most potent malaria vectors, *Anopheles gambiae*, from Africa to South America and Southeast Asia. Such an event occurred in the 1930s when *A. gambiae* was accidentally introduced to Brazil. A vigorous campaign to identify breeding areas and eradicate larvae was required during the 1930s and 1940s to avert a near disaster (Parmakelis et al., 2008). More sophisticated analyses of locational influences on malaria are vital to several current international initiatives aimed at halting the spread of malaria, including the Multilateral Initiative on Malaria, which is part of the United Nations Children's Fund, United Nations Development Programme, World Bank, and World Health Organization Special Programme for Research and Training in Tropical Diseases.[1]

ROLE OF THE GEOGRAPHICAL SCIENCES

Traditionally, epidemiologists allocate risk for specific diseases such as cancer to specific causes, including willingness to participate in high-risk behaviors (e.g., smoking), nutritional status, age, genetic predisposition, and gene–environment interactions. Studies are usually based on experiments (e.g., case-control studies, cohort studies) aimed at evaluating whether a specific factor is associated with an increased risk of disease. Although useful, this approach often fails to take into account the range of locational influences that affect diseases or the temporal and spatial complexities that arise from disease latency and individual mobility through the life course. The geographical sciences have a role to play in addressing such matters. Building from an early focus on disease patterns, the geographical sciences are devoting attention to the development of models and visualizations that provide insight into space-time influences on health and disease (Jacquez et al., 2005a,b; Meliker et al., 2005). These models and visualizations

[1]See www.mimalaria.org (accessed January 20, 2010).

help geographical scientists account for the impacts of exposure to potentially hazardous substances in different places (Meliker and Jacquez, 2007). Geographical scientists are also exploring ways of using remote sensing (satellite data and hyperspectral imagery) in the study of disease location and spread (Goovaerts et al., 2005; Avruskin et al., 2008).

The geographical sciences add at least four dimensions to the investigation of disease incidence and response, and of conditions such as drug addiction (Thomas et al., 2008). First, they provide a series of techniques suited to the detection of patterns and anomalies in the incidence of disease, and to their interpretation in terms of disease-spreading and disease-causing mechanisms. From the earliest successes achieved by John Snow in unraveling the etiology of cholera (Johnson, 2006) to modern techniques for detecting statistical significance in apparent clusters (O'Sullivan and Unwin, 2003), a vast amount of pure and applied research has gone into the examination of health and disease patterns, and their connection to other circumstances and processes in the human–environment system (Cromley and McLafferty, 2002; Waller and Gotway, 2004; Koch, 2005). Second, geographical science tools allow researchers to ask questions about the factors present in an area that correlate with disease outcomes, whether as causes or as statistical correlates. Geographic information systems (GIS) have proved valuable in this regard because they support a range of multivariate analyses and can be used to analyze the impacts of factors at different scales. Third, geographical scientists have developed spatially explicit models of disease spread that incorporate concepts such as distance and connectivity directly into the models, often in the form of cellular automata[2] (Schiff, 2008) or as agent-based models (Maguire et al., 2005). Finally, the concern of the geographical sciences with location promotes consideration of access to health care. When facing conditions such as heart attacks, the distance between the patient and the emergency room and the ability to get to the emergency room quickly can literally be the difference between life and death. Geographical scientists have found dramatic impacts of differentially located health care facilities, at scales that range from the global to the local (e.g., O'Meara et al., 2009), and they have developed a range of techniques for optimizing the location of facilities to achieve desirable goals (e.g., Rushton, 2003).

Much health research makes use of statistical techniques to make general conclusions from samples of laboratory animals or patients. When these experiments are controlled, by choosing random samples and giving them identical treatments, the conditions conform precisely to the assumptions made in standard statistical tests. In such cases significance levels can be determined, and results generalized to the populations from which the samples were randomly drawn. However, in research focused on actual fine-scale geographical patterns rather than controlled conditions, these assumptions are rarely valid (O'Sullivan and Unwin, 2003). Analysis at the national level often uses health statistics aggregated to the county or even state level—units of analysis that have their origins in previous centuries, vary enormously in size, and average or smooth out much of the actual variation that occurs at smaller scales. These statistical issues provide examples of the substantial problems confronting health researchers that the technical arsenal of the geographical sciences can help resolve. The following questions illustrate the types of research that allow the geographical sciences to contribute to the development of a multidisciplinary synthesis, which is needed to tackle major health issues in the years to come.

RESEARCH SUBQUESTIONS

How do diseases respond to changes in ecosystems and climate?

Spatial distributions of diseases are seldom uniform, and understanding the reasons for their heterogeneity can lead to valuable insights. As our ability to conduct spatial and temporal analysis has improved, so has our ability to characterize both sides of the disease equation—the genetics of diseases themselves and human risk factors. Advances in spatial and temporal analysis are also facilitating efforts to respond to changes in the human–environment system.

On the genetic side, new insights into how and why diseases emerge and sometimes lead to pandemics such

[2]Cellular automata models attempt to simulate processes operating across geographical space by dividing the space into a set of normally rectangular cells and applying a series of rules to those cells to approximate changes in each cell's state through time, in response to the state of neighboring cells as well as to external factors.

as HIV and influenza can be achieved by coupling the study of molecular and spatial analysis. One example of this type of inquiry is a study on H5N1 avian influenza that analyzes genetic change using a spatial approach (Figure 6.2). As part of the study, a spatiotemporal influenza genotype database was built and integrated with ecosystems factors using GIS. The diffusion of different H5N1 genotypes and mutations that are related to virulence is being tracked, and the impacts of human–environment ecosystem factors (e.g., human population distributions, farming systems, land use, climate) on H5N1 viral evolution are being measured using a spatial analytical approach called ecological niche modeling. Similar efforts for other viruses can help identify the human–environment ecosystems in which viruses change.

Climate change can have substantial impacts in the area of health, affecting, for example, the emergence and resurgence of vector-borne diseases (those diseases such as malaria or West Nile virus that are transmitted to humans, animals, or plants via an insect or other organism). A recent National Research Council report states that "nearly half of the world's population is infected with at least one type of vector-borne pathogen" (NRC, 2008c). With climate change potentially expanding the spatial reach of vector-borne diseases by increasing flooding, altering precipitation patterns, and raising temperatures, there is a need for research that explores the link between climate change and such diseases.

A robust earth observing system that monitors key climate variables is critical to predicting future disease outbreaks. Anyamba et al. (2009) propose using satellite measurements to examine the linkage between climate variability and the outbreak of Rift Valley fever in the Horn of Africa. Their work examines the relationship between outbreaks of the disease, which affect animals and humans, and the El Niño/Southern Oscillation. They conclude that satellite observations can be used to map climate changes, which in turn can be used to predict the location of outbreaks. Like Rift Valley fever, outbreaks of malaria, yellow fever, or

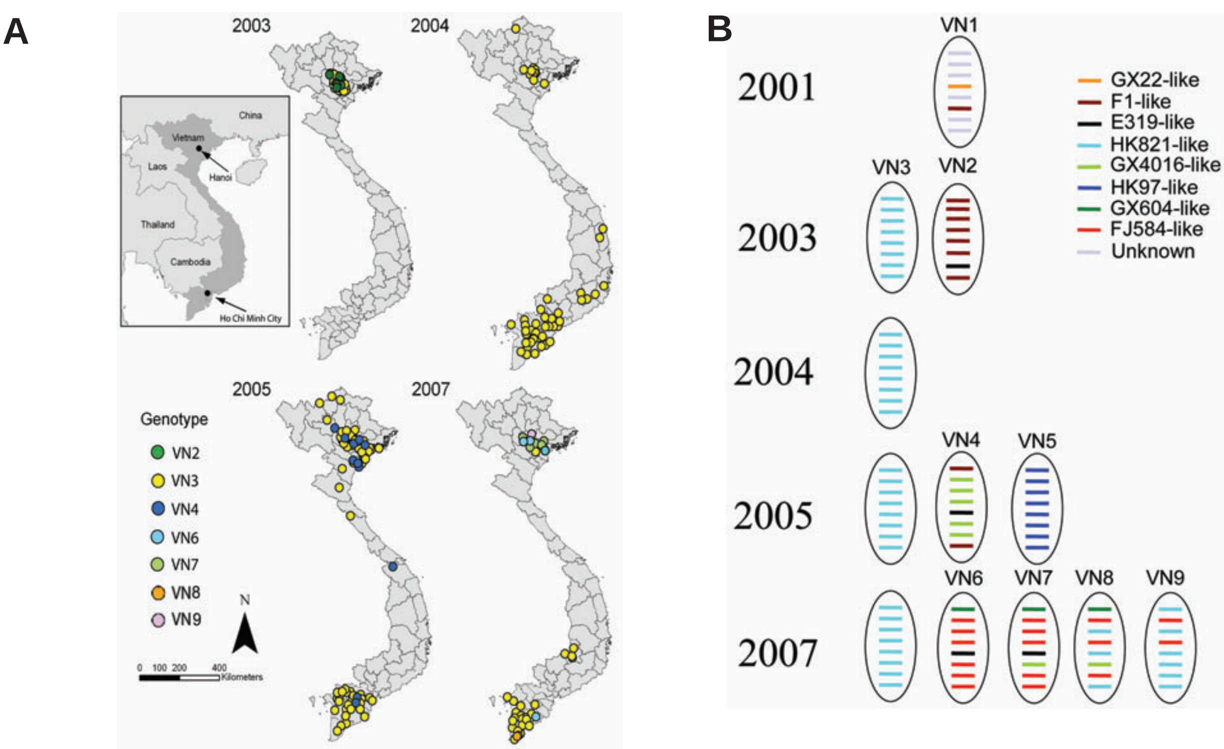


FIGURE 6.2 (A) Geographical distribution of the genotypes identified for 142 H5N1 viruses isolated in Vietnam from 2003 to 2007, with the viral genotype of each H5N1 isolate mapped chronologically to show the time of genotype isolation in different regions of Vietnam. (B) Emerging H5N1 genotypes from introduction and reassortment in Vietnam from 2001 to 2007, showing the genetic change of each H5N1 virus segment using a different color corresponding to its precursor virus—a sort of family tree for the virus. SOURCE: Michael Emch, University of North Carolina, Chapel Hill Geography. Used with permission.

dengue fever are not just public health events; they are environmental, economic, and ecological as well. The geographical approach adopted in the Rift Valley fever study could advance understanding of the relationship between climate change and vector-borne disease outbreaks more broadly.

Climate change could also affect the risk to humans of noninfectious diseases such as melanoma. Melanoma is known to be caused by exposure to ultraviolet (UV) radiation. Ethnicity is a risk factor (epidermal melanin is protective), as is location (altitude, latitude), occupation (indoor, outdoor), and individual behaviors (e.g., outdoor lifestyle). Climate models predict highly spatially heterogeneous changes in UV radiation as a function of atmospheric CO_2 doubling (Figure 6.3). Future research is needed on the impact of different climate change scenarios on melanoma incidence using the time-dependent locations of individuals coupled with models of climate change and of melanoma risk.

How do disparities in geographical access to health care affect health and well-being?

The locations, number, and quality of health care providers differ from place to place, and services may not be available in places where they are most needed. Access to health care is not simply a matter of measuring distance to health facilities; access is affected by socioeconomic status, cultural and social norms, and transportation networks. In a study of access to gov-

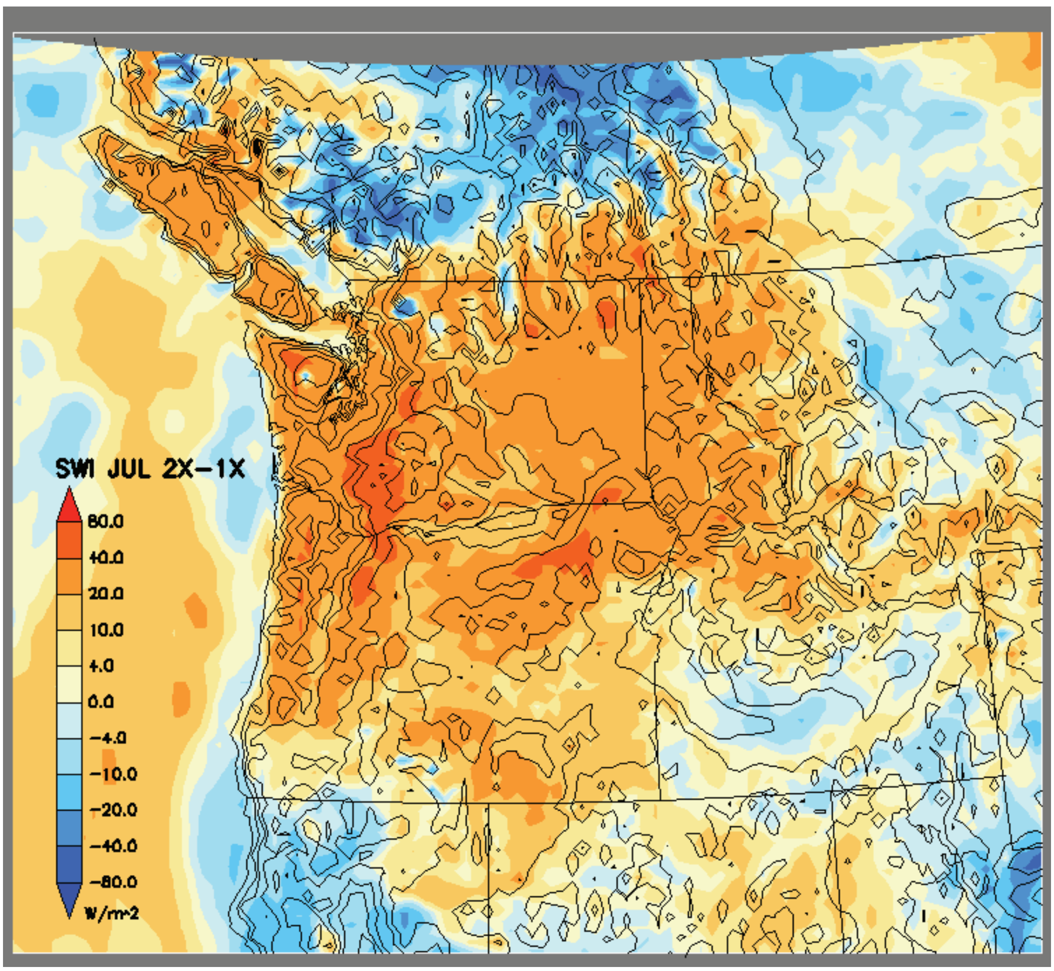


FIGURE 6.3 Simulated changes in July incident solar radiation over the Pacific Northwest expressed as the difference between doubled and present atmospheric CO_2 concentrations (2x-1x). SWI: incoming solar radiation (W/m^2). The model was configured with a horizontal grid spacing of 15 km and 23 layers in the vertical. Solid black lines indicate U.S. state borders and elevation. SOURCE: Courtesy of Steve Hostetler and Justin Holman.

ernment health services in Kenya, for example, Noor et al. (2006) show that a transportation model adjusted for actual use patterns and competition between health facilities provided a much better indicator of access to health care than did a model focused solely on distance. Their example illustrates that understanding the locational circumstances that create inequalities in access to health care is a critical piece of the health picture.

Studies analyzing geographical inequalities in health care access should build on increasingly detailed work on this topic. For example, Luo and Wang (2003) have developed an index of spatial accessibility as a way of analyzing the local supply of primary health services in relation to local demand. Their method was used to analyze spatial access to primary care in Illinois and its relationship to late-stage cancer (Wang et al., 2008). Not surprisingly, in Illinois, as in much of the United States, rural areas are characterized by lower levels of spatial access to primary care than urban areas (Figure 6.4). But why are some rural communities much more disadvantaged than others? Geographical scientists such as Cutchin (1997) have taken up this question, looking at the specific attributes of rural places that tend to attract primary-care physicians and encourage them to stay. Additional work in this vein can provide policy makers and community planners with much needed insight into ways of addressing the problem of rural health care access.

Another example of the promise of spatially explicit studies of health care access comes from ongoing research on whether cancer patients living in communities with poor access to primary health care have a higher-than-average risk of late-stage diagnosis (cancer diagnosed after it has spread to distant tissues or organs; Figure 6.5). The researchers conducting the study undertook multilevel analyses of the associations between late-stage risk, individual demographic variables, and contextual variables, describing socioeconomic characteristics of places and their spatial access to primary care (McLafferty and Wang, 2009). Their research showed that, in Chicago, the high risk of late diagnosis among cancer patients largely reflects the high concentration of vulnerable people living in economically disadvantaged neighborhoods. Outside Chicago, poor spatial access to primary care significantly heightens the risk of late diagnosis among breast and colorectal patients, supporting the findings of geographical scientists in other

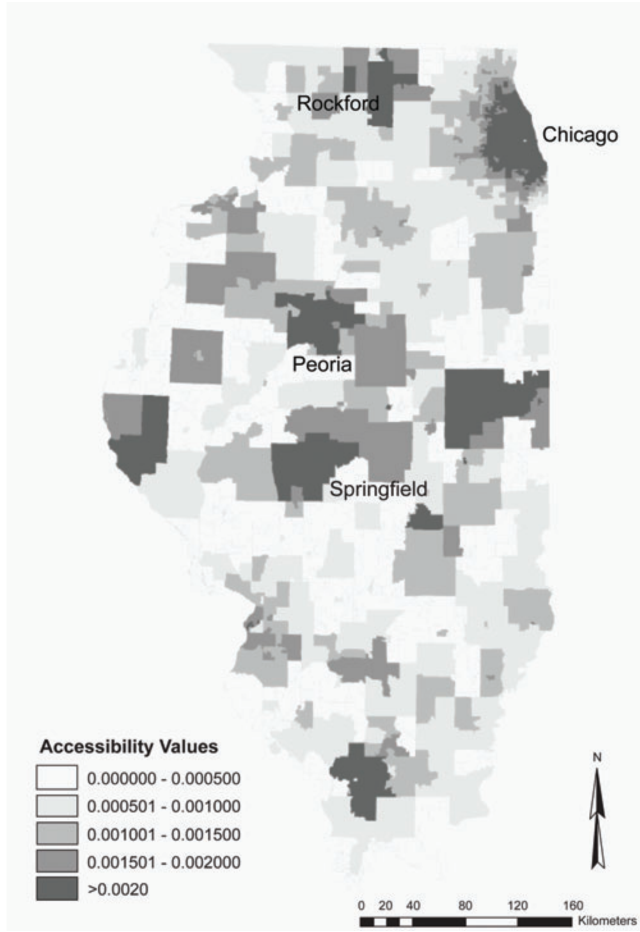


FIGURE 6.4 Spatial access to primary care in Illinois by ZIP code based on the 2-Stage Floating Catchment Area method. Light tones indicate poor spatial access to primary care. The map was created as part of a study examining the combined effects of spatial access and socioeconomic factors on breast cancer diagnosis. The results showed that poor geographical access to primary health care had significantly increased the risk of late diagnosis. The study also showed that spatial access to primary health care was more important than similar access to mammography. SOURCE: Wang et al. (2008).

contexts (Rushton et al., 2004). McLaffery and Wang also identify poor health outcomes in a dense urban setting where spatial access to care is quite high, according to GIS-based measures.

These findings highlight the need for research investigating the connections between population vulnerability, place vulnerability (Chapter 3), and access to health care. Among the most important topics to investigate are effects of time-space constraints on the use of primary health care by low-income urban residents

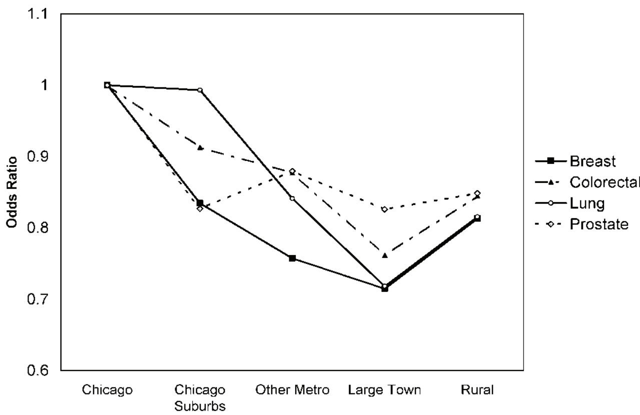


FIGURE 6.5 Variation in risk of late-stage cancer diagnosis for the four major cancers in Illinois. The figure shows that risk is highest for cancer patients living in Chicago. The odds of late diagnosis decrease away from Chicago, reaching their lowest levels among patients living in large towns (defined here as towns with populations ranging from 10,000 to 50,000 and not located in metropolitan areas). This figure does not control for age or race, but the study looked at the impacts of both and found that the rural-urban gradient remained consistent for breast, colorectal, and lung cancers, but disappeared for prostate cancer. SOURCE: McLafferty and Wang (2009).

and geographical variations in the quality of health care. There is also much to be gained from comparative analyses of the spatial dimensions of health care access in different parts of the world and for different types of health challenges (e.g., heart disease, HIV/AIDS, vector-borne diseases).

How are social factors affecting the spread of diseases, such as HIV/AIDS in Sub-Saharan Africa?

HIV/AIDS is the leading cause of death in Sub-Saharan Africa, which remains the epicenter of the epidemic, accounting for 67 percent of all people living with HIV worldwide and 72 percent of all AIDS-related deaths (UNAIDS, 2008). In southern Africa, the worst-affected region, national adult prevalence exceeds 15 percent in seven countries. Women account for nearly 60 percent of HIV infections in Sub-Saharan Africa, and young women represent 67 percent of all new cases of HIV among people ages 15-24 living in developing countries (UNAIDS, 2008).

It is well established that spatial variability is a key factor in understanding HIV/AIDS; geographical concentrations of HIV/AIDS are found even in many countries with very low HIV prevalence. In the Democratic Republic of the Congo, for example, Messina et al. (In review; Figure 6.6) documented a high degree of spatial variability in HIV/AIDS cases and found that the distribution of the disease was influenced by such social factors as sexual practices, socioeconomic status, and access to transportation. Future work in this vein could describe the spatial distribution of genetic subtypes of the HIV/AIDS virus, which in turn could facilitate the effort to understand not only where imported cases originate, but where and how those cases evolve from earlier strains. Work on the impacts of socioeconomic status on the distribution of

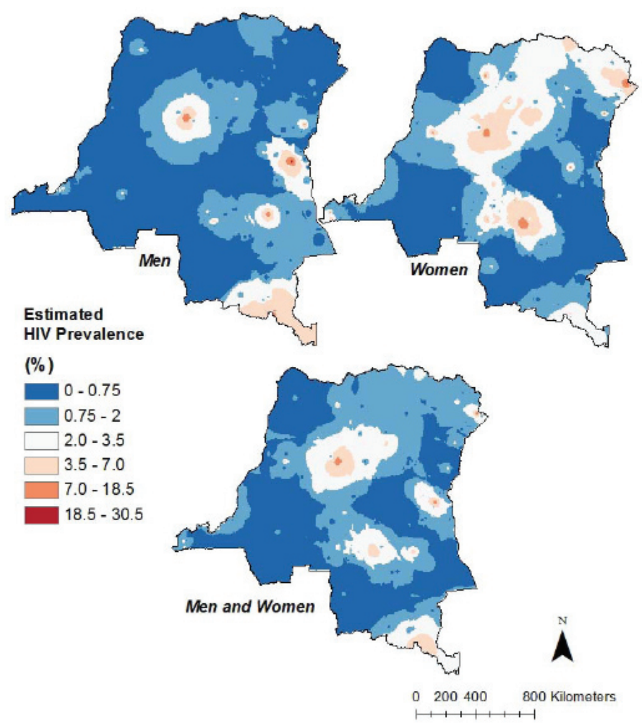


FIGURE 6.6 HIV distribution in the Democratic Republic of the Congo, showing differential patterns for men and women. A geographically based, population-representative sampling scheme allowed Michael Emch and his colleagues to construct this visualization, which was then used to examine the impacts of social factors on the distribution of HIV/AIDS. Not surprisingly, the study found that social factors are the most important drivers of the distribution of the disease. SOURCE: Michael Emch, University of North Carolina, Chapel Hill Geography. Used with permission.

cholera in Bangladesh confirms the value of this type of approach (Emch et al., 2010).

There is a long tradition of work on this subject in the geographical sciences (Gould, 1993), but the range of contextual influences needs to be expanded. It is becoming clear that more attention needs to be paid to the influence of attitudes toward sex, female empowerment, and economic inequities on the spread of diseases (Kalipeni et al., 2007). Additional work focused on developing and analyzing data on the spatial distributions of HIV/AIDS and relevant social circumstances can improve understanding of the range of influences on the vulnerability of different people in different places (Kalipeni et al., 2007, 2008).

Globalization and migration are also changing sexual practices in Africa (Ampofo, 2001; Spronk, 2005). As a result of globalization, the media, including cinema, television, and the Internet, provide Africans with new sexual imagery, and undermine traditional boundaries of sexuality and sexual expression. Further research is needed on where these changes are having the greatest impacts, and how they are affecting the spread of HIV/AIDS. Work in this vein could also provide a more detailed understanding of the role of migrant labor on the diffusion of HIV/AIDS (Bassett and Mhloyi, 1991; Jochelson et al., 1991; Hunt, 1996).

Governance is another social factor affecting the spread of HIV/AIDS in Africa and elsewhere. Relatively little attention has been paid to the effects of civil wars and political instability on HIV/AIDS. As victims of armed conflict and as refugees (or internally displaced persons), women and children are particularly vulnerable to sexual violence and abuse. Warring factions often use rape as an expression of violence and revenge against their enemies (Kalipeni and Oppong, 1998). In refugee camps, women and girls remain subjects of sexual coercion; separated from their families and living as internally displaced persons or refugees, survival compels many individuals to engage in transactional sex with other refugees or the host population (Spiegel and Nankoe, 2004). The volatile mix of refugees, soldiers, desperate women with children, and the chaos associated with war facilitates HIV/AIDS spread, but how this plays out in different places is not well understood.

The efforts of multilateral organizations, such as UNAIDS, have focused on assisting governments to deal with the challenge of HIV/AIDS rather than evaluating how the apparatus of government—whether democratic, autocratic, or chaotic—affects HIV/AIDS spread. Yet government leadership, particularly good governance, expressed by effective administration of international aid for HIV/AIDS control, and public health programs including antiretroviral access, influence the success or failure of HIV/AIDS control efforts, as do policies that address poverty and social inequalities. Including such matters in a broadened effort to look at contextual influences on the geographical spread of HIV/AIDS can enhance understanding of how and why disease diffusion patterns are different from place to place.

SUMMARY

The geographical sciences have a role to play in advancing understanding of spatial variations in the spread of disease, access to care, and the treatment and prevention of illness. The tools and approaches of the geographical sciences can provide insights into locational factors affecting health, and they can illuminate important contextual influences on the diffusion of diseases. A major initiative to build upon and expand work in the geographical sciences on health matters would benefit efforts to combat disease and promote human well-being.

7

How Is the Movement of People, Goods, and Ideas Transforming the World?

Without the movement of goods, people, and ideas, cities falter, economies wane, and societies wither. As local economies and their associated land uses have become more specialized, mobility has grown ever more central to the sustainability of human activity. Economic specialization, which has fueled productivity growth and propelled the dispersion of interlinked activities worldwide, is premised upon various forms of mobility, including the migration of labor from low-wage to high-wage places, the daily travel of workers from their homes to workplaces, the movement of materials to worksites, and the distribution of finished products to markets. When mobility ceases, as in the case of a natural disaster, not only do workplaces fall idle, but also people cannot get emergency medical attention, families cannot obtain food, and social gatherings of all sorts are canceled or postponed.

The increasing importance of mobility to local, regional, and global economies and to everyday life is reflected in data showing the relentless increase in many measures of the movement of people and goods (Figures 7.1 and 7.2). In the United States, the movement of people and freight has been steadily increasing.[1] At the international scale, human migration more than doubled between 1970 and 2000, with the largest proportion of migrants moving to countries in the developed world (Figure 7.2; Clark 2006a), and climate change is likely to accelerate these trends (see special issue of *Forced Migration Review,* 2008).

The evidence of steadily increasing mobility runs counter to the claim that distance—and the movement required to overcome it—no longer matters because of high-speed information and communication technologies (ICTs; e.g., Cairncross, 1997). If ICT has rendered distance irrelevant, as suggested by the death-of-distance hypothesis, then people and businesses should have little reason to incur the time and money costs involved in moving themselves or goods over increasingly greater distances. People would rely primarily on the keyboard and mobile phone to reach destinations of interest, and measures of mobility would fall. Although ICT has had impacts on physical movements at the scale of daily travel and may have affected migration streams (e.g., via the outsourcing of software development and call centers to India), the nature of the impacts is complex and generally has not conformed to predictions associated with the death-of-distance hypothesis (Mokhtarian, 2003; Janelle, 2004).

Persistent upward trends in mobility reflect rising affluence in some cases (as in the United States) but can also exacerbate differences among places (as when people move from rural areas to cities); in addition, rising mobility is associated with escalating conflict in some instances (as in refugee flows) and can produce high levels of urban congestion. Because of the strong links between motorized movement and petroleum consumption, ever-increasing mobility also raises concerns about greenhouse gas emissions. Transportation

[1] One exception is residential mobility, which has declined in recent decades. The proportion of the U.S. population that changed residence in any given year has fallen from about 20 percent in the 1950s and 1960s to 12-13 percent in recent years (2006-2008). See www.census.gov/population/socdemo/migration/tab-a-1.xls (accessed January 20, 2010).

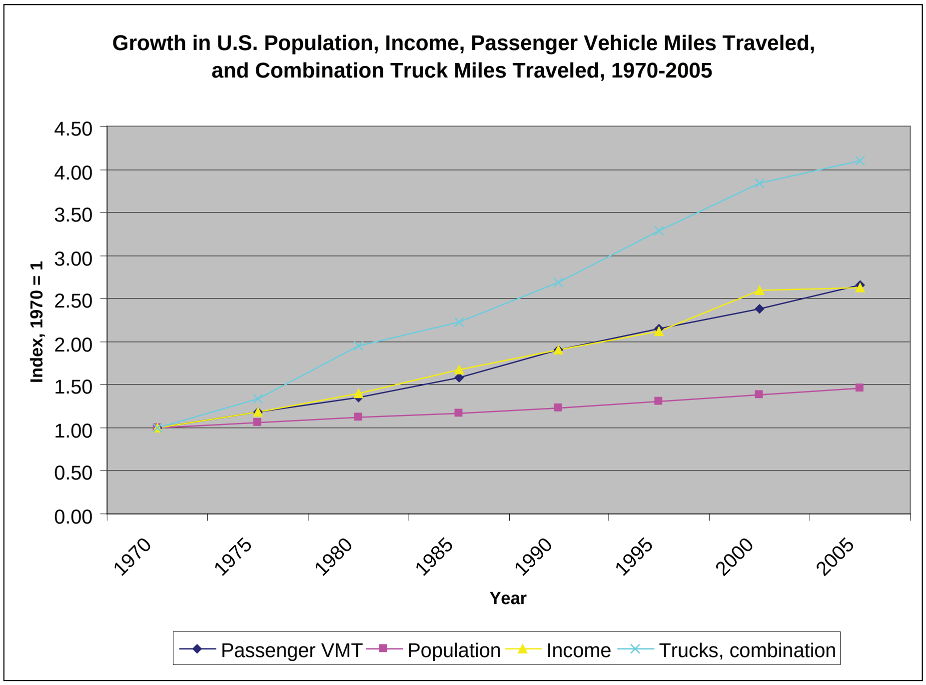


FIGURE 7.1 The rise in passenger vehicle miles traveled (VMT) since 1970 in the United States closely tracks increasing incomes but well exceeds population gains. In the United States, passenger VMT in 2005 was more than 2.5 times VMT in 1970 whereas population grew by a factor of only 1.5. Worldwide, passenger travel (kilometers traveled) more than quadrupled between 1960 and 1990 and is expected to more than quadruple again by 2050 (Schafer and Victor, 2000). NOTE: "Trucks, combination" combines all vehicles with two or more units, one of which is a tractor or straight truck power unit. Miles-traveled statistics are for highway travel. SOURCES: Passenger VMT data from National Transportation Statistics, Table 1-32; population statistics from U.S. Census Bureau (2007), Table 2; combination truck statistics from Federal Highway Administration (annual series), Table VM-1.

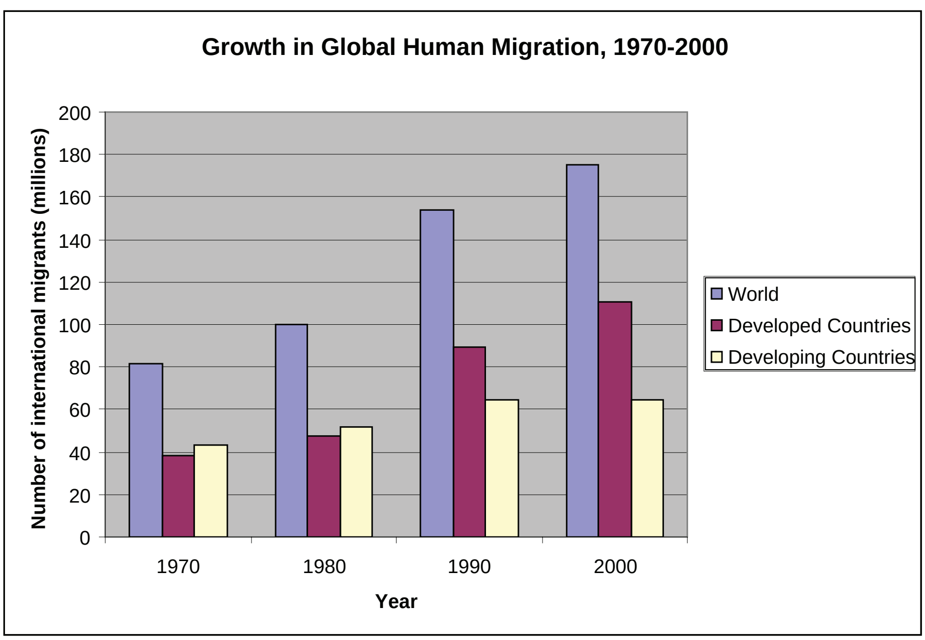


FIGURE 7.2 The total number of international migrants in the world increased steadily between 1970 and 2000, with an increasing proportion of such migrants moving to developed countries as migration destinations. SOURCE: Adapted from International Organization for Migration (2005).

accounts for about one-third of the U.S. carbon emissions stemming from energy use. The reliance of the transportation sector on petroleum and its significant contribution to carbon emissions places mobility on geopolitical and climate change agendas.

ROLE OF THE GEOGRAPHICAL SCIENCES

Geographical patterns of human activity, such as settlement patterns or the locational arrangements of manufacturing or services, are shaped by patterns of mobility. With expertise in analyzing connections between spatial patterns and processes, the geographical sciences investigate the causes and consequences of mobility at varying spatial scales. Early work established that increases in accessibility provided through expansion of, and improvements to, the road network fundamentally altered the settlement system; as travel speeds increased, larger places grew, whereas smaller places declined and sometimes disappeared altogether (Garrison et al., 1959). Underscoring the relationship between mobility and land-use patterns, research has also demonstrated that improved access via expanded road capacity leads to increased traffic flows (Sheppard, 1995), which further reinforce differences between and among places. Moreover, some of those impacts are felt in places that are quite distant from the network segments that were improved (Giuliano, 1995). A remaining research challenge is to understand how to increase accessibility without exacerbating the traffic congestion that now plagues cities around the world.

Research has begun to identify the specific aspects of places that are salient to mobility processes and will therefore determine how increasing mobility will change the world differently in different places. Research to date suggests that the causes and consequences of increasing mobility will continue to have certain common threads across places, while also differing in important ways from place to place. However, much remains to be learned about the reasons for and outcomes of those differences.

The spatial separation of specialized land uses—such as food stores or city parks at the local scale or the manufacture of magnetic recording heads for 30 percent of the world's computer hard drives in Dongguan, China (*The Economist*, 2008) at the global scale—makes economic specialization and scale economies visible on the landscape. Relatively inexpensive and dependable mobility from the local to the global scales has enabled this form of spatial organization to become truly global, with high levels of specialization twinned with long-distance linkages integrating the global space-economy (Dicken, 2003). Because connectivity varies from place to place (Figure 7.3), these mobility-based globalization processes have contributed to the patterns of inequality discussed in Chapter 8.

Place-specific policies can play a role in shaping the nature of the relationship between geographical pattern and process. At the intraurban scale, Giuliano (1995) showed that the land-use impacts of transportation investments are highly variable from place to place because they depend on local economic and political conditions. For example, the light-rail transit (LRT) built in Buffalo, New York, in the 1970s, failed to revitalize that city, whereas Portland, Oregon's LRT has been central to a suite of policies that have supported the continued vibrancy of Portland's city center and helped increase the share of travel made via public transit. Similarly, Mountz (2004) documented how international migration flows, specifically those involving human smuggling, are influenced by the micro decisions of immigration bureaucrats in destination places. Her ethnographic study of the differential receptiveness of places within Canada to immigrants illustrates the importance of governance practices and structures at national and provincial levels.

Geographical technologies, especially geographic information systems, facilitate the tasks of analyzing place-specific dimensions of mobility patterns and processes at varying spatial scales. At the regional level, the adoption of such technologies by planning agencies has transformed the ability of planners to create optimal designs and communicate projected impacts of different planning scenarios to the public (Nyerges, 2004). At the individual level, the rapid adoption of Global Positioning System (GPS) technologies is altering the mobility of vehicle drivers, pedestrians, and cyclists. Still largely missing are comparable systems for wayfinding indoors, as in large retail complexes, and for helping the visually impaired, such as "talking signs." The potential impacts of the widespread adoption of these technologies are substantial. For example, if everyone is capable of finding a destination, then the destination need not advertise its location or adopt

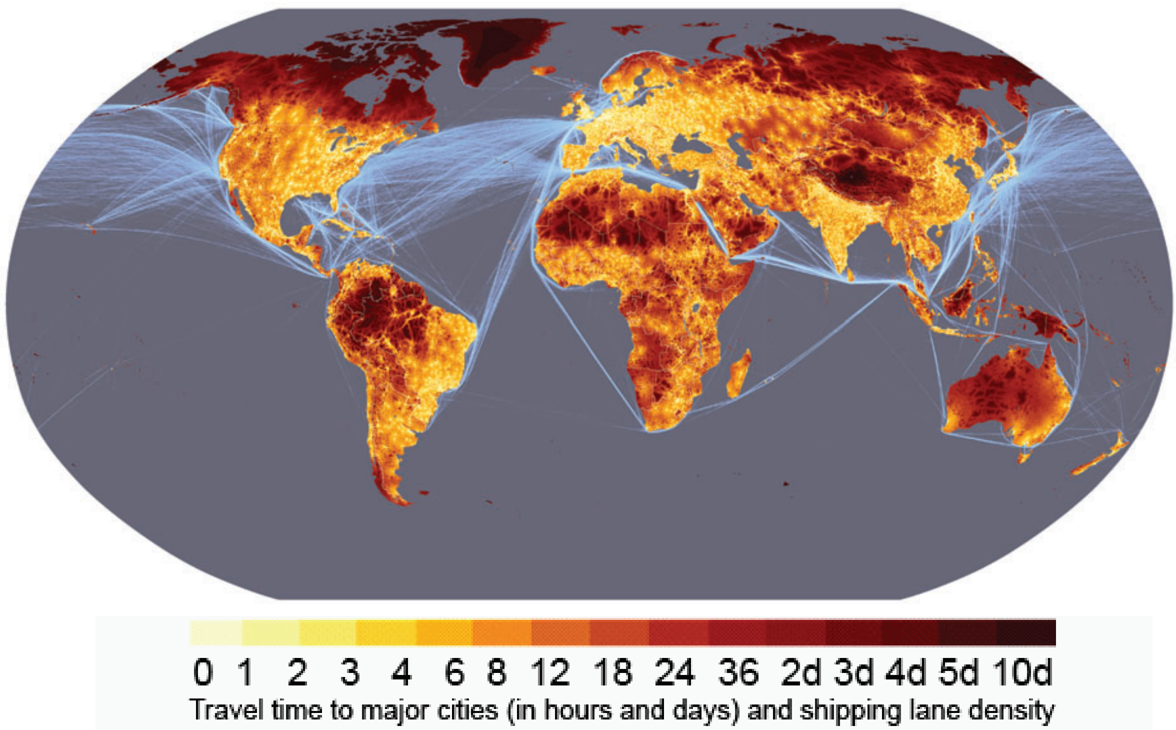


FIGURE 7.3 Global accessibility map showing that the time needed to travel to a city of 50,000 or more population varies substantially. The map shows that only 10 percent of the world's land area is more than 2 days' travel by land or water from a city of that size. Imagine the accessibility differences that would become apparent by creating other maps like this at different scales and with other access criteria, such as distance to a city with a population of at least 100,000. SOURCE: © European Commission, 2008.

a location that is prominent in the landscape, such as a street corner. The following research questions provide examples of the types of movement and mobility issues the geographical sciences are particularly well positioned to investigate.

RESEARCH SUBQUESTIONS

How does virtual interaction reflect and alter the organization and movement of people, goods, and ideas in geographical space?

Just as physical mobility has been increasing in many different ways, so has virtual interaction via the Internet, telephone, videoconferencing, e-mail, cell phones, and text messaging. Despite initial predictions that virtual interactions via ICT would eliminate or substantially reduce the need for movement, research indicates that these forms of interaction are complementary and synergistic, rather than substitutable; in some cases ICT increases rather than decreases mobility (Mokhtarian and Meenakshisundaram, 1999; Mokhtarian, 2003). In the business world, face-to-face contact remains the most essential form of interfirm interaction (e.g., Cook et al., 2007), with e-mail, telephone, and videoconferencing used to supplement rather than replace face-to-face interactions. Because of the importance of face-to-face communication for these firms, business success depends on geographical, not virtual, proximity to other firms, giving rise to a daily movement of workers to dense clusters of firms that fosters growing traffic congestion.

Research has begun to address the dynamic relationship between virtual interaction and the movement of people and goods. Understanding this relationship will be necessary for designing policies aimed at reducing energy consumption, managing urban congestion, and cutting greenhouse gases. Schwanen and Kwan (2008) showed that the ways in which ICT affects individuals' movements depend on context (type of activity undertaken, place, time, technologies available). The primary impact appears to be that mobile ICT

allows for more temporal flexibility in the scheduling of activities, whereas the Internet allows for greater spatial flexibility of activities, especially work and shopping. As new forms of ICT, especially mobile ICT, are more widely adopted, research can illuminate which kinds of physical movements are most affected and how; for example, such technology can enable new forms of ride sharing that could reduce carbon emissions.

The geographical sciences are also well positioned to assist industries with finding optimal ways to combine increasingly important virtual interaction with the persisting importance of grounded contacts. For example, Aoyama and Ratick (2007), using data from a nationwide survey of logistics firms and from interviews they conducted with logistics providers and users in the northeastern United States, found that although the use of ICT tools is widespread, traditional trust-based relationships remain fundamental to logistics operations.

Research points to the value of examining the complex dependencies between virtual and physical forms of interaction. Further research is needed on how specific aspects of places (e.g., settlement density, cultural norms, network configurations) affect the relationship between virtual and physical mobility. A combination of geographical approaches, including time-space studies of human movement in different environments, can illuminate how, for example, increasing road congestion or energy costs are likely to change the ICT-mobility relationship or how new forms of ICT, including the deployment of GPS systems in cell phones, might alter the ICT-movement relationship. Understanding how the rapidly evolving forms of virtual interaction reflect and alter the organization and movement of people, goods, and ideas in geographical space will require detailed, geospatially referenced information at the levels of the person, household, and firm. One promising avenue is the use of data from cell phones equipped with GPS units; such data have proved effective in measuring the spatial dimensions and intensity of social interactions (Eagle et al., 2009).

How do changing energy costs influence the movement of people and commodities and the geographical organization of the landscape?

The global economy is dependent on cheap, abundant energy. Articles published in 2008 in the *New York Times* and *Washington Post* argued that sharply increased fuel costs had curtailed global supply chains and challenged the just-in-time delivery process that manufacturers worldwide have come to rely on (Cha, 2008; Rohter, 2008). The newspaper stories tell of several manufacturers that had recently shifted their operations from China to the United States because of large increases in shipping costs (from approximately $3,000 in 2000 to approximately $8,000 in 2008 for a 40-ft container), which had come to trump China's lower labor costs. Following classical economic geography theory (Weber, 1929), the industries that are most likely to relocate and restructure when shipping costs skyrocket are those, such as steel and furniture, that produce goods that are high in bulk or weight relative to their selling price.

Relatively little is known about how the mobility behavior of U.S. firms and consumers might respond to sustained, significant price increases in energy. The historical record is not helpful because the United States has not experienced the kind of prolonged, substantial price increase in petroleum that might lead to altered mobility and land-use patterns. The rapid and dramatic, but relatively short-lived, price increases following the oil embargo of 1973 led to a minor, temporary dip in the mobility-growth curve shown in Figure 7.1, and the main midterm impact was the consumer shift to smaller, more fuel-efficient vehicles. Comparisons with Europe, where higher taxes on fuel have made energy more costly than in the United States, are of limited use because the distances to be traversed are far greater in the United States (in part because energy has been so relatively inexpensive) and because mobility patterns are to a large degree culturally specific; the norms in Europe, regarding, for example, bicycling or the use of public transit, differ substantially from those in the United States.

Geographical research can provide important insights into how changing energy prices are likely to affect the movement of people and goods, the interaction of virtual and physical forms of mobility, and the geographical organization of the landscape. Such analyses are not likely to be straightforward, however, because the parameters of the relationships involved are dynamic and place specific, and considerable uncertainty surrounds people's response to increasing energy prices. Economic theory suggests, for example, that as

the cost of transport rises relative to income, mobility will be curtailed, but recent evidence does not support this contention. Hughes et al. (2008) compared consumers' sensitivity to increases in gasoline prices in 1975-1980 with those in 2000-2006 and found that the short-run price elasticities for gasoline were significantly lower in 2000-2006, indicating that to effect a reduction in gasoline consumption, much higher price increases will be needed. Whereas these authors model the overall demand for gasoline in the United States as a function of price, geographical scientists can, by disaggregating demand spatially, determine how such price elasticities are related to the geographical characteristics of different places. Spatial analysis that is sensitive to place differences can also demonstrate the range of likely impacts of energy price increases on people's residential choices and daily travel patterns.

How is migration reshaping local communities, labor markets, and ethnic and national identities?

Migration is a form of mobility that entails a change in residential location and can involve moves from the intraurban to the global scale. Although rising incomes and the ease of communication and return migration have made such moves less difficult for some people, the fears and realities of epidemics and terrorism have rendered migration far more difficult for others, including Muslims, refugees, and people from areas with high rates of HIV/AIDS or Avian flu. Fences in Israel and at the U.S.-Mexico border stand as proof that some borders are hardening, while the relatively recent freedom of movement for workers within the European Union is evidence of other borders softening (Figure 7.4).

Migration changes people, and it changes places. A change in location often brings with it a change in personal identity, with potentially major implications for politics in the receiving place. When migrants who have moved either short or long distances differ from residents in the receiving community, their arrival, especially in large numbers, brings change to that community, whether it is a neighborhood or a nation. In a world of relatively cheap travel, instantaneous communication, and deep divisions among people, contemporary migration poses new challenges to understanding these impacts. Among these challenges are the increasing circularity of migration, in which people return with some regularity to their place of origin, the greater ease of sustained communication with people in the home place, and the speed with which changes in one part of the world are felt via refugee and migrant flows in other parts of the world.

Researchers have traced the impacts of migration on people and communities. In a study of Dalit circular migration within and beyond India, Gidwani and Sivaramakrishnan (2003) demonstrated that migration alters migrants' identities by broadening their experience and increasing their sense of agency. In the high-income countries of North America, Europe, and Asia, immigration is a topic of great debate, especially as it affects receiving communities. Within the United States, for example, workers have voiced concern that the presence of immigrants depresses wages and takes jobs away from the U.S.-born labor force. Research has not yet settled this debate, however. Using data from Los Angeles, Ellis and Wright (1999) demonstrated that because immigrants and nonimmigrants tend to work in different types of jobs, with newly arrived immigrants and U.S.-born migrants to Los Angeles channeling into non-overlapping sets of industries for work, the presence of immigrants does not lower the wages of, or take jobs away from, U.S.-born workers. In contrast, others have documented a variety of immigrant impacts on native-born workers, including wage reduction (Borjas, 2006) and the movement of native-born workers out of industries that become immigrant-intensive (Altonji and Card, 1991).

Whether migration is linked to altered or unchanged identities will vary from place to place; comparative research can tease out the commonalities in these place-based relationships, which have strategic importance for migrant well-being as well as for political stability at various spatial scales (see Chapter 9). Research has shown how the ethnic makeup of migrant receiving communities can affect migrant identities and migration outcomes (e.g., Western, 2007). Migration can also lead to hardened identities. In a study of rural-to-urban migration in Ecuador, Lawson (2002) found that, owing to the racism and economic hardship that migrants encountered in the city, they tended to retain their ethnic and regional identities from their rural places of origin. This finding is important because these migrants did not identify with other poor people in the city or join

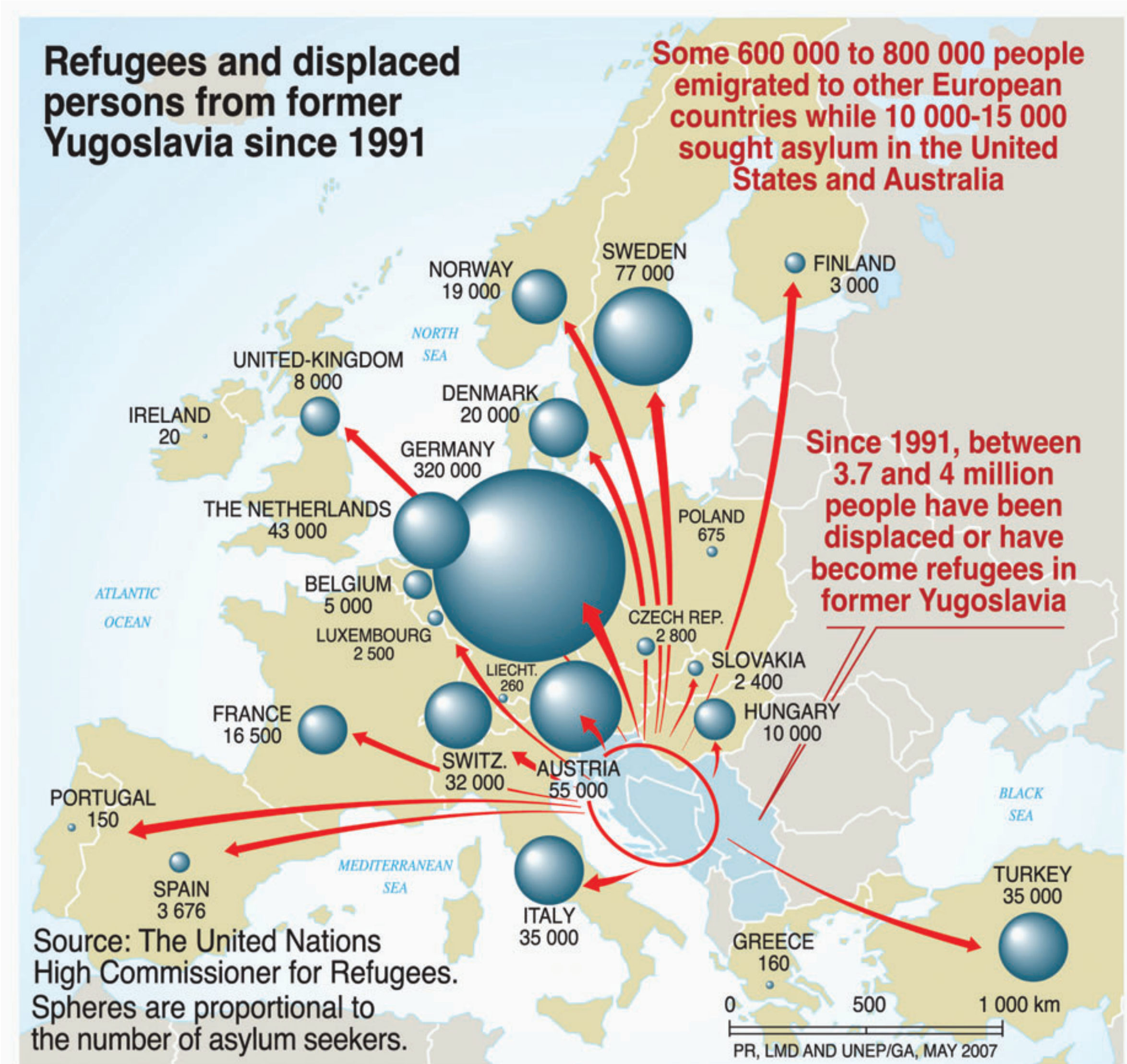


FIGURE 7.4 Refugees and displaced people from the former Yugoslavia since 1991. There have been nearly 800,000 people who have left the former Yugoslavia since 1991. SOURCE: United Nations High Commissioner for Refugees.

with them to work for improved living and working conditions. The ethnic composition of a migrant's receiving community affects not only identity but also the degree of segregation among different groups and differences in income levels. Musterd et al. (2008), using longitudinal disaggregate data (1995-2002) from Statistics Sweden, discovered that whereas living in a neighborhood with high concentrations of co-ethnics is initially a boon to migrant incomes, such clustering can soon become a disadvantage. Moreover, the employment status of neighbors from other ethnic groups can have an impact, which is often positive if neighbors are employed but negative if they are not. Additional studies along these lines can identify which characteristics of the local residential environment matter most to migrant outcomes and to the receiving community as a whole.

Where are the greatest points of vulnerability in the transportation network and what are the implications of disruptions at those points of vulnerability?

Mobility depends on integrated, well-maintained transportation networks. Although transportation networks have become denser in many parts of the world,

in the United States some network segments have been pruned back in recent decades. In the Great Plains, for example, many rural roads have been abandoned, in part because of declining rural population densities in some areas and in part because of the increasing costs of maintaining older infrastructure such as bridges. As networks are rationalized, the remaining ones become more vulnerable because there are no alternatives in the event of failure or attack. This problem is especially apparent in the rail network, which has been drastically thinned as the system has modernized and become more cost-conscious, to the point that in some areas the network now lacks almost all redundancy.

Ports are especially vulnerable points in the nation's transport network. Assessing the impacts of losing major port facilities to disaster and identifying potential alternative trade facilities should be two high-priority research topics. The ports of Los Angeles and Long Beach, for example, handle nearly one-quarter of U.S. total exports and 40 percent of all containerized cargo import traffic, a trade volume equal to $256 billion in 2005 (BST Associates, 2007). The importance of these ports to the national economy is further underlined by the fact that more than 60 percent of the cargo arriving there is destined for markets outside Southern California (BST Associates, 2007), and two-thirds of exports originate outside California (POLA/POLB, 2008).

The geographical sciences can also contribute to identifying the greatest points of vulnerability in the U.S. transportation network and document the impacts that would follow should mobility through those vulnerable points be lost. A recent National Research Council report, *Potential Impacts of Climate Change on U.S. Transportation* (NRC, 2008b), called attention to the vulnerability of transportation infrastructure to climate change, concluding that the most vulnerable places are likely to be in coastal regions. That committee's first recommendation was, in part, for governments to "inventory critical transportation infrastructure in light of climate change projections to determine whether, when, and where projected climate changes . . . might be consequential" (p. 192). Transportation networks are vulnerable to far more than climate change, however, and the need to assess network vulnerabilities and their consequences extends well beyond coastal areas.

The analytical tools of the geographical sciences are well suited to this task. Work by Peterson and Church (2008) provides an example of both the potential and the current limitations of such research. Using rail network data from Oak Ridge National Laboratories and freight data from the Bureau of Transportation Statistics,[2] they developed a rail routing model to assess the loss of a rail bridge. Their analysis showed that, for all traffic going to and from Washington state that used the Sandpoint Bridge, the detours—upon the loss of the bridge—averaged 330 miles. Impedances increased as well, indicating that the selected detour routes were not ideal. Because the national rail dataset lacks data on track capacity, this study was not able to take this important variable into account. Because some routes are already operating at capacity, some freight might not be transported or trains could be forced to take even longer routes if the Sandpoint Bridge became impassable.

SUMMARY

Understanding how and why mobility and mobility consequences vary systematically from place to place will be crucial for predicting the range of likely economic, environmental, social, and political impacts of increasing mobility and altered mobility choices in the coming decades. Geographical scientists from several disciplines, including geography, civil engineering, sociology, economics, and political science, are well positioned to take up these questions.

[2]See www.bts.gov/publications/national_transportation_statistics/ (accessed January 20, 2010).

8

How Is Economic Globalization Affecting Inequality?

We live in an unequal world in which descriptors of global inequality—especially inequalities in income—abound. "[T]he world's richest 500 individuals have a combined income greater than that of the poorest 416 million . . . 2.5 billion people [are] living on less than $2 a day" (Watkins et al., 2005: 18). Researchers and policy makers continue to debate how, and at what scale, inequality trends are changing, but, by any measure, the disparities between rich and poor are striking (Firebaugh, 2003; Milanovic, 2005; *The Economist*, 2006; Held and Kaya, 2007; Lobao et al., 2007). The recent past has also seen rapid economic globalization—characterized by the supranational spatial integration of economies and societies (Stiglitz, 2002). Globalization has intensified flows of goods, finance, people, and political/cultural interactions all across our planet (Mittelman, 2002; Dicken, 2007). Understanding the nature of, and linkages between, globalization and inequality is crucial because disparities abound in access to needs such as shelter, land, food and clean water, sustainable livelihoods, technology, and information. Inequalities in all of these realms pose challenges to human security and environmental sustainability.

Much of the research on the link between globalization and inequality has focused on the global scale—looking at inequality between countries using aggregate economic indicators such as gross domestic product per capita (sometimes weighted by national population). These measures of global inequality are limited because they implicitly assume that within-country distributions of income are perfectly equal (Milanovic, 2005). Comparisons of inequality across individuals in the global population, and across a broader range of measures, regardless of national boundaries, are much rarer, but are increasingly possible and necessary (Milanovic, 2005). Beyond the need for improved measures of global inequality, we are currently witnessing a historic change in patterns of inequality, termed by Firebaugh (2003) as the "inequality transition." Since the 1980s, evidence suggests that inequalities have increased more rapidly within countries than between them, heralding the reversal of increasing between-country inequality—a trend that began with the Industrial Revolution (Milanovic, 2005; Held and Kaya, 2007).

Because it may seem counterintuitive that subnational inequality would grow in an era of globalization, this finding points to the importance of research on scale differences in inequality patterns, and on the spatial impacts of specific aspects of economic globalization, so that we can better understand how globalizing processes influence inequality—where and for whom (Kanbur and Venables, 2007). Addressing this problem requires research aimed at identifying how distributional mechanisms within markets and governance arrangements are shaping inequality across geographical scales and differentially distributed populations (see Lobao et al., 2007).

The timing of the recent shift in inequality patterns (the early 1980s) corresponds with the rise of new forms of economic globalization that have transformed spatial relationships around the globe. Expanding transportation and communication networks, trade liberalization, reorganization of financial structures, and the rise of new

regional trade agreements have been redefining flows of commodities, investments, labor, and political power across the globe (Murray, 2006; Dicken, 2007). In the process, the "where and who" of the winners and losers of globalization are changing, as is the traditional role of the state in economic governance. The state is no longer the only, or even the primary, actor in economic processes, because markets are now global, regional, and local as much as they are national (O'Loughlin et al., 2004). A key research challenge going forward, then, is to move beyond a focus on individual states and identify the relationships between globalization and shifting patterns of inequality at varying scales (Held and Kaya, 2007).

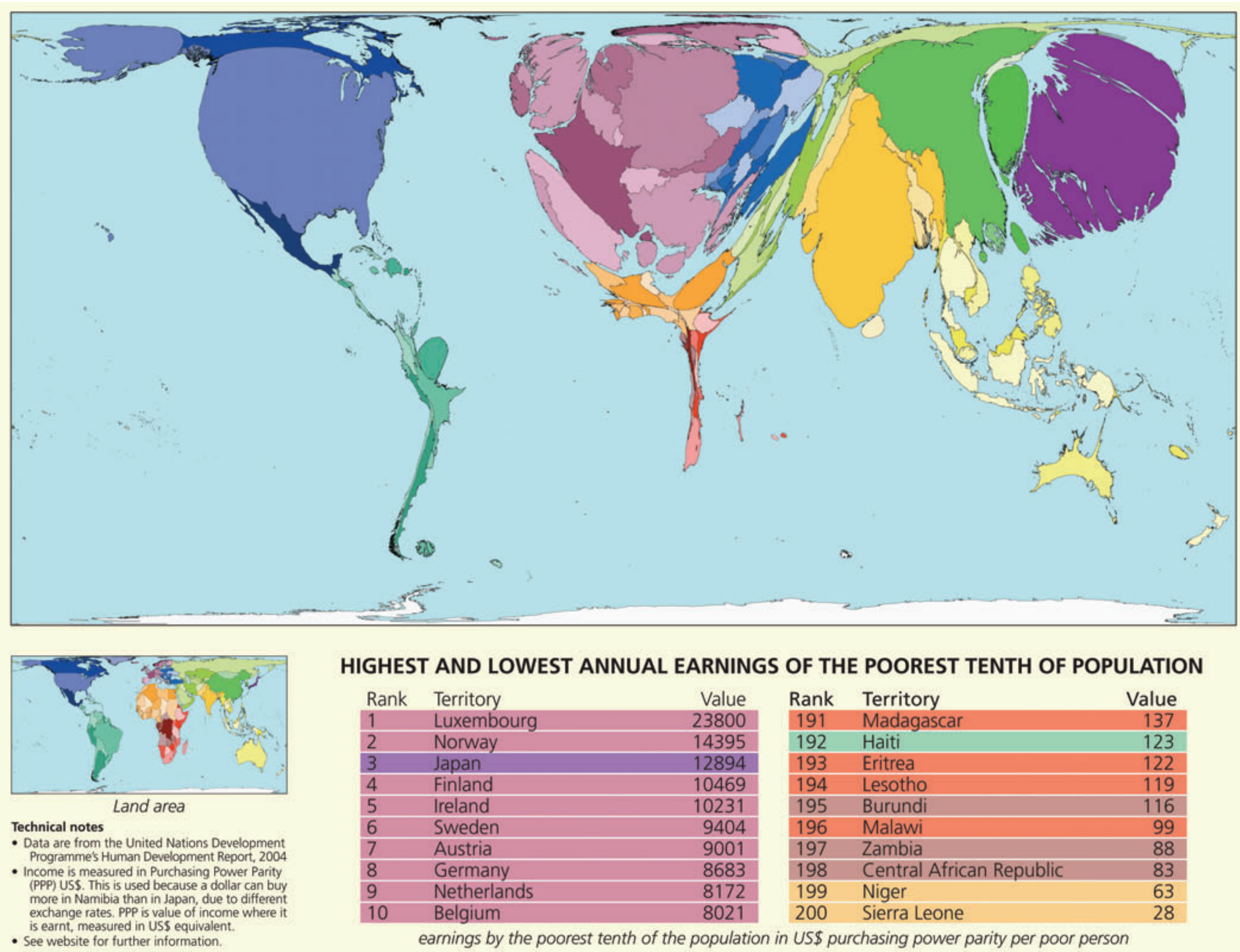
ROLE OF THE GEOGRAPHICAL SCIENCES

Research in the geographical sciences can help identify the patterns and processes producing inequality across the world—within states and at local levels. Although sociology takes inequality to be a central problem, Lobao et al. (2007) argue that too much sociological research on inequality still operates at the national scale and entails questionable geographical assumptions about both the causes and patterns of inequality. These scholars argue for "the systematic incorporation of spatial factors into theory and research on inequalities" (Tickameyer, 2000: 811) and for research that builds multiscale models and draws on spatially referenced data. Geographical scientists are at the forefront of this research, undertaking projects aimed at representing and analyzing the intersections between the spatial and social dimensions of inequality. For example, geographical research is providing innovative cartographic representations of inequality that shed light on the nature and significance of patterns of inequality (Figure 8.1).

Research in what has been termed the "new economic geography" is currently analyzing the spatial character of inequality by building structural models of the relations between economies of scale, transport costs, geographical remoteness from markets, and biophysical resource endowments (Krugman, 1993; Redding and Venables, 2004). The 2009 World Development Report adopts this frame of analysis to argue that three geographical dimensions of the global economy must be transformed to reduce inequality. The report argues that these reductions will result from (1) a greater concentration of economic activity (density), (2) a reduction in the friction of distance (i.e., increasing the mobility of goods, capital, and labor), and (3) diminished divisions between places as a result of borders and differences in language and regulations (World Bank, 2009: 7). Research in the geographical sciences extends the new economic geography (see Part I, Box 1), positing the fundamental importance of place-based influences on economic developments. It follows that policy makers need to focus more attention on local contextual influences, a point highlighted by Kates and Dasgupta (2007: 16749). Along the same lines, Sachs (2006: 73) notes that "policy makers and analysts should be sensitive to geographical, political and cultural conditions that may each play a role (in producing poverty)."

In their efforts to understand uneven development within and across places, geographical scientists have developed a body of work focused on the spatially variable operation of processes producing inequality in places characterized by different systems of macroeconomic regulation, different welfare regimes, different social divisions of labor (between paid and unpaid work, for example), and different consumption and distribution practices (Jones and Kodras, 1990; Smith, 1990; Kodras and Jones, 1991; Perrons, 2001). Research in this vein, which has been undertaken by geographically oriented researchers in demography, geography, economics, and political science, has shown that inequality emerges from multiple processes operating simultaneously at a range of spatial scales, including unequal global distributions of returns to production and work at sites along international production and consumption chains; regional trade agreements that limit national sovereignty on environmental and labor protections; and the presence of race and gender discrimination in different places (Nagar et al., 2002). Their findings are of relevance to debates about the economic and inequality impacts of market liberalization (see generally Firebaugh, 2003; Milanovic, 2005; Dicken, 2007; Kanbur and Venables, 2007).[1]

[1]Some scholars take the position that market liberalization is a necessary precursor to expanded economic opportunities for all people across the globe (World Bank, 2009). Others contend that international trade agreements (North American Free Trade Agreement, World Trade Organization) that limit the ability of governments to adopt a wide range of protective environmental and social policies contribute to inequality (Stiglitz, 2002).



Rank	Territory	Value	Rank	Territory	Value
1	Luxembourg	23800	191	Madagascar	137
2	Norway	14395	192	Haiti	123
3	Japan	12894	193	Eritrea	122
4	Finland	10469	194	Lesotho	119
5	Ireland	10231	195	Burundi	116
6	Sweden	9404	196	Malawi	99
7	Austria	9001	197	Zambia	88
8	Germany	8683	198	Central African Republic	83
9	Netherlands	8172	199	Niger	63
10	Belgium	8021	200	Sierra Leone	28

earnings by the poorest tenth of the population in US$ purchasing power parity per poor person

FIGURE 8.1 This cartogram resizes national territories by the earnings of the poorest 10th living in each territory, focusing attention on comparative issues of importance for research on space, scale, and inequality. By visualizing the relative scope of inequality across major regions, questions are raised about the causes of similarly deep inequality in both Latin America and Africa vis-à-vis the countries of the Organisation for Economic Co-operation and Development. Striking spatial patterns such as these point to the potential importance of common social and economic histories that situate each of these regions in particular ways within global divisions of labor, commerce, politics, and cultural flows. SOURCE: Worldmapper. Copyright 2006 SASI Group (University of Sheffield) and Mark Newman (University of Michigan).

Systematic comparisons of subnational inequality and its causes across a range of countries, and in the context of global processes, could move the research agenda forward. Prior research has compared patterns and processes of within-country inequality for Britain, the United States, South Africa, and the former Soviet Union to determine how different economic structures, institutional arrangements and processes of discrimination (apartheid, class, gender and race) are associated with distinct patterns of spatial and social inequality (Smith, 1987). Smith's comparative research is now 20 years old, however, and we lack an adequate understanding of how recent developments are changing economic, social and political landscapes as a result of global financial instability, new global trade regimes, and environmental instability in the wake of the transition from socialist to capitalist, globalized economies in some parts of the world (cf. Mykhenko and Swain, 2010, who provide a contemporary example of research on the links between territorial inequality, post-socialist transition, and the importation of foreign capital).

Studies by Dicken (2007) and Leichenko and O'Brien (2008) in particular highlight the value of focusing on the specific mechanisms of globalization and the role they play in shaping who and where the winners and losers of globalization are found. Their work points to the importance of analyzing the inequality outcomes of international trade treaties, global environmental regulations, global regulations on investments and the activities of transnational corporations, as well as spatial variations in labor standards and laws. Yet to date, the inequality impacts of these seismic shifts in global institutional and societal processes have not been systematically compared as they play out between and within countries around the globe (Murray, 2006; Dicken, 2007). In the next 10 years, researchers will have access to decennial census data and household income surveys (from many countries) that will allow them to represent and understand the spatial and scalar dimensions of inequality—both between and within countries during a period that will likely be characterized by intensifying globalization and economic instability. Against this backdrop, the investigation of the following research questions would be particularly productive.

RESEARCH SUBQUESTIONS

What patterns of inequality are emerging at the subnational scale?

A long tradition of geographical work focuses on developing visualizations of spatial patterns that can facilitate deeper understanding of sociospatial processes. Cartographic representations of inequality across countries and scales reveal current patterns of winners and losers in the face of globalization processes. For example, Glasmeier's *Atlas of Poverty in America* (2005) identifies regions in distress: Appalachia, the Mississippi Delta, areas where indigenous people are concentrated, and much of the U.S.-Mexico border region. Drawing on state, county, and metro-scale socioeconomic data across four decades, the *Atlas* represents the social and spatial dimensions of poverty within each region and identifies vulnerable populations of children, women-headed households, and minorities. This detailed mapping of poverty over time suggests relationships between places and people, raising analytical questions about the intersections of gender, household structure, race/ethnicity, place, and poverty in different parts of the United States (Figure 8.2). This within-country representation of variables associated with poverty provides a model for the type of comparative spatial analyses that are needed across countries.

New geographical visualization techniques also offer insights into linkages between inequality and the multiple consequences of globalization. Professor Danny Dorling's team at the University of Sheffield is developing geovisualizations of social spatial structures (at a range of scales) that allow the research community to pose new questions about how people's life chances are distributed and how are they changing (Figure 8.3).[2] This research group has also developed a series of virtual atlases using flow lines and multidimensional scaling to visualize global city networks (see Figure 8.3). These visualizations demonstrate how fast Internet connectivity for some people and places changes their possibilities for engaging globalization processes, with different implications for places that remain relatively disconnected.

The digital divide in Internet connectivity could influence the ways in which places are understood in the future, as volunteer geographical information becomes increasingly central to the collection of georeferenced data about our world. Those cities and countries that are relatively underresourced in technologies, relevant education, and Internet connectivity will be poorly represented in terms of data accuracy or the range of information available (elaborated further in Chapter 11 of this report). In the future, teams of researchers could use geovisualizations to model uncertainty in inequality patterns that may result from distinct scenarios of globalization. By representing the possible impacts of global connectivity and isolation, they could inform policy decisions about the implications of connectivity and isolation for access to key resources (land, water, energy, etc.), engagement with the global economy, and environmental alteration at the subnational level (Smith, 1987; Murray, 2006; Moseley and Gray, 2008).

Where and how does market liberalization exacerbate or reduce spatial inequalities?

Market liberalization has been a central facet of globalization since the 1980s. Market liberalization

[2]See www.sasi.group.shef.ac.uk/ (accessed January 20, 2010).

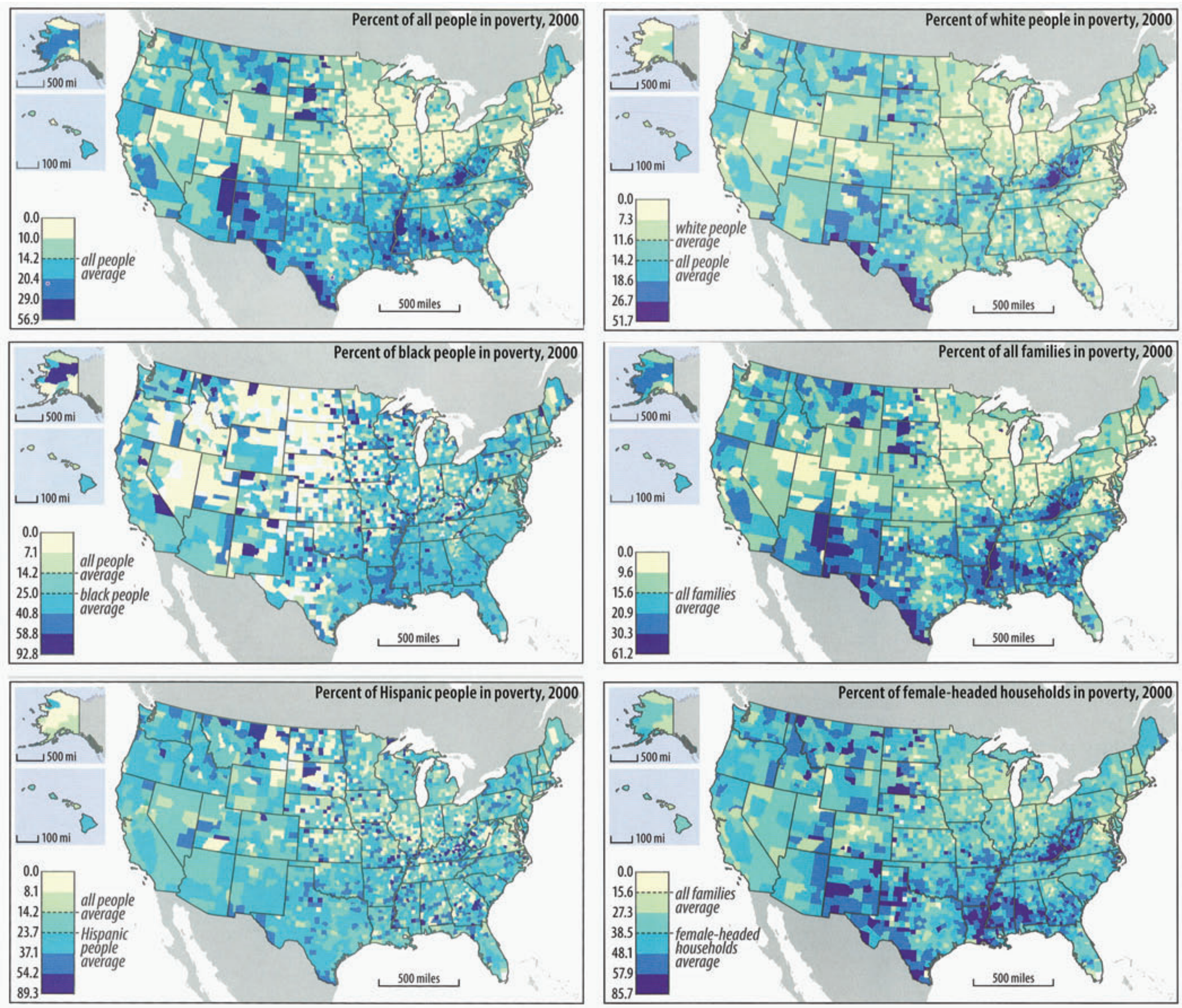


FIGURE 8.2 A map series showing the spatial distributions of different populations in poverty in the United States. SOURCE: Glasmeier (2005).

entails the global integration of trade and capital markets through free trade agreements and changes in national trade and financial regulations such as tariff barriers and capital controls. These liberalization processes, along with exuberant lending, overconfidence in monetary policy (as an effective control on money and credit supplies), and floating currencies, brought both high economic growth rates and considerable economic turbulence, with dramatically different impacts for different people and places (as in the Latin American debt crisis of the 1980s, the Asian financial crisis of the 1990s, the global financial crisis of 2008; Krugman, 2000). Market liberalization has also led to a reworking and intensification of networks of connectivity between many cities; an expanding role for transnational corporations in global production and consumption networks; and the large-scale privatization, and international ownership, of telecommunications, transport systems, and primary resource extraction in low-income countries (Dicken, 2003).

In recent years, geographical research has yielded important insights into the social and spatial trade-offs

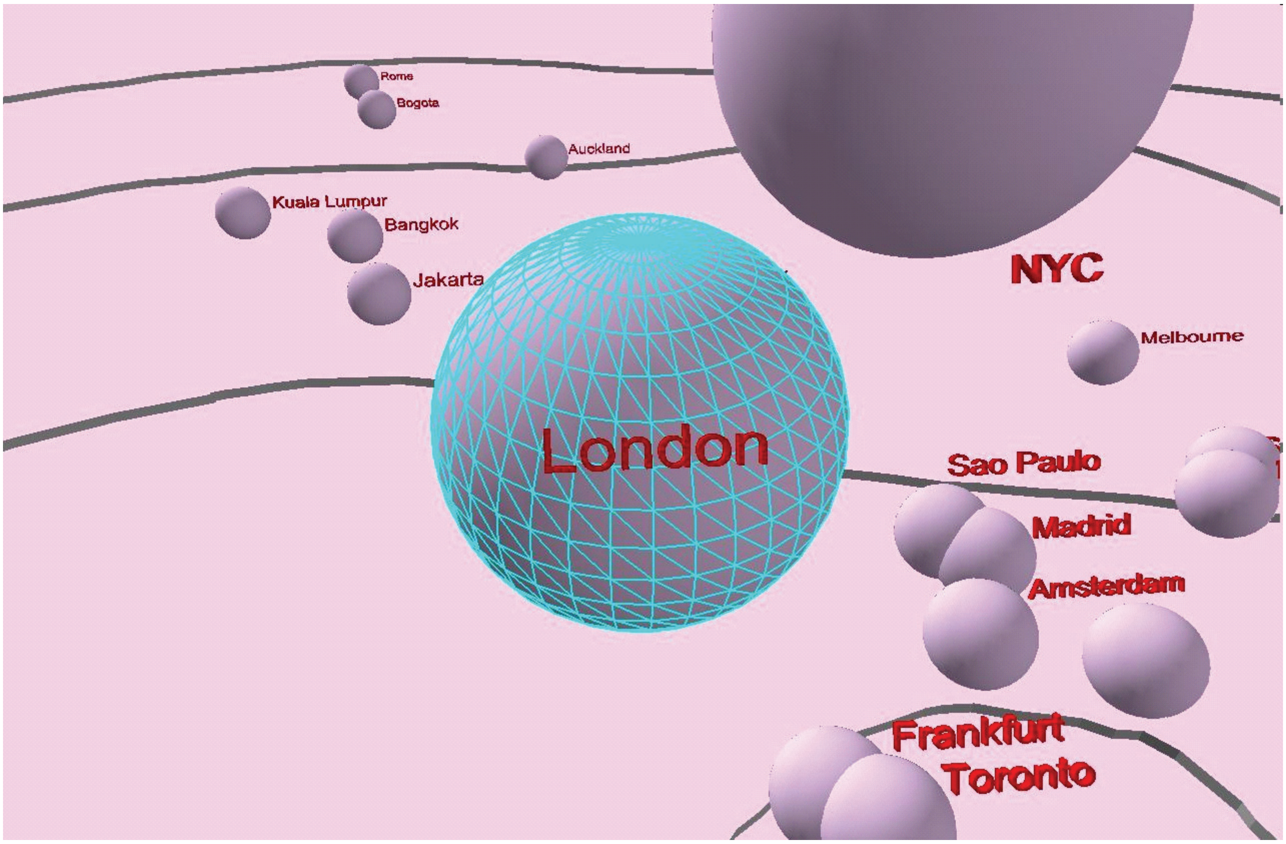


FIGURE 8.3 City connection map that demonstrates how "close" other cities are to London in a virtual space of relationships based entirely on connection values. SOURCE: Social and Spatial Inequalities. Used with permission.

between trade liberalization and inequality (including research focused on economic growth, environmental change, and human vulnerability). For example, Leichenko and O'Brien (2008) have exposed patterns of advantage and harm in agricultural communities in India in the face of twinned processes of market liberalization and climate change. Their work begins from the premise that the inequality effects of global processes have distinct spatial and social expressions (see also Sachs, 2006; Kates and Dasgupta, 2007). Drawing together data on climate impacts on crop yields, changes in plant pollination and competition, and human vulnerability to climate change, Leichenko and O'Brien (2008) constructed maps revealing the regions that are most vulnerable to predicted climate changes across the country (see also the discussion of this study in Chapter 3). A geographic information system analysis of the relationship between that map and patterns of agricultural export advantage, import sensitivity, and the resilience of farmers to socioeconomic change allowed them to identify places across India that are "double exposed" to climate change and trade liberalization and places that are less exposed, and therefore are likely to be less vulnerable in the face of these processes (Figure 8.4).

Similar methodologies and tools can be employed to analyze the changing geography of inequality in the face of the twin impacts of market liberalization and climate change (Liverman and Vilas, 2006). Research in this vein will require the construction of integrated datasets from existing national and international sources at a range of spatial scales, including production and trade data, household income surveys, national census data, and United Nations and World Bank data (see Ravallion, 2001; Redding and Venables, 2004). These new datasets can be employed to produce targeted sectoral and regional analyses of understudied economic sectors (e.g., industry and energy systems in the tropics), which in turn can pave the way for research exploring the ways in which a variety of key economic sectors are influenced by global trade and

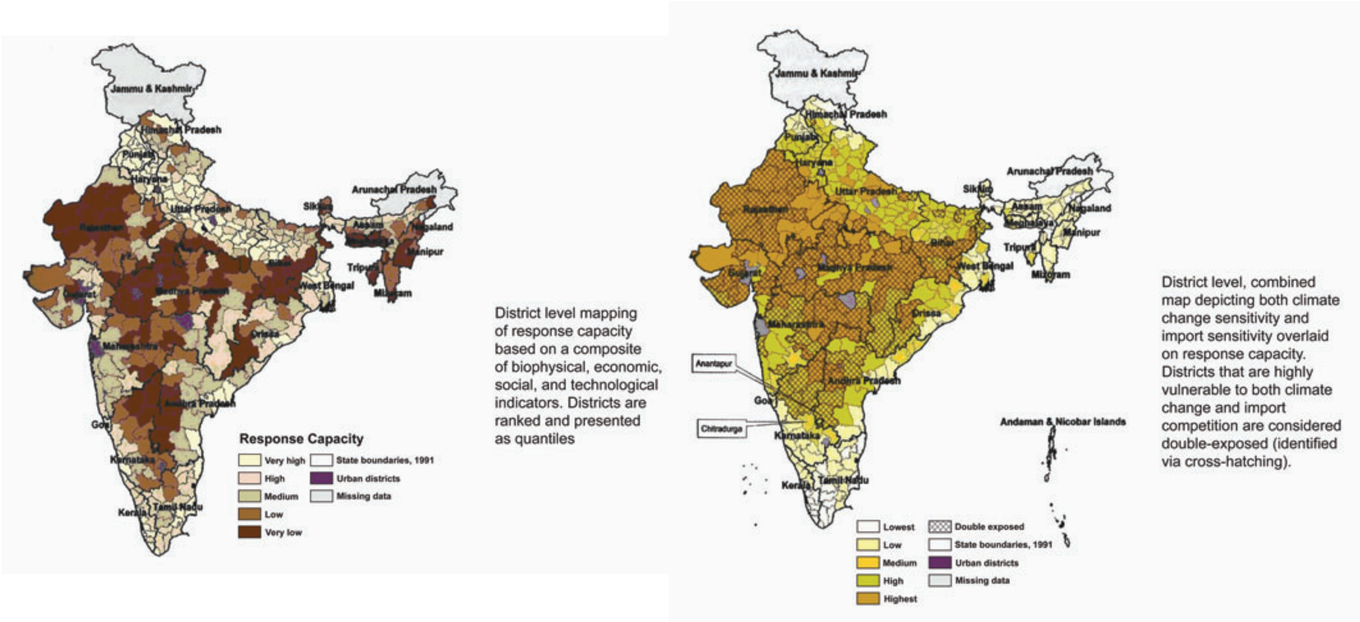


FIGURE 8.4 Maps depicting district-level response capacity and sensitivities to climate change and import competition. SOURCE: Leichenko and O'Brien (2008).

capital flows in ways that produce shifting landscapes of production, consumption, and vulnerability (Liverman, 2008).

How are poverty, wealth, and consumption interrelated across space and at multiple geographical scales?

Differences in wealth and poverty are often not solely the result of local circumstances; they are produced by relationships that link far-flung places. Geographical scientists investigate how spatial relationships shape inequality, such as the relationships between production in low-income countries and rich-country consumption, or the inequality effects of deploying agricultural lands for domestic foodstuffs or for export crops. They have developed conceptual and analytical tools for tracing the networks of production, consumption, and exchange that link people across world markets and for identifying the processes through which wealth and poverty are explicitly linked. Of particular significance is work on (1) production chains—linked sequences of place-based functions where each stage adds value to the commodity (Dicken, 2007); (2) consumption chains—links between consumption and the conditions of production (Hartwick, 1998); and (3) global commodity chains, which expose prices, and the geographical distribution of value, at each node along the production and marketing trajectory of a specific commodity (Gereffi and Korzeniewicz, 1994; Leslie and Reimer, 1999).

Geographical research on commodity chains is enchancing understanding of the ways in which inequality is reworked through production and consumption linkages. For example, Nepstad et al. (2005) have traced how consumers in high-income countries shape the nature of agricultural commodity chains through an examination of the globalization of soy and beef industries based in the Brazilian Amazon. They developed a network analysis that connects growing fears of bovine spongiform encephalopathy (BSE or mad cow disease) in ration-fed beef in the United States and Europe with increasing demand for grass-fed beef from the Amazon. Their work demonstrates how conditions of production are reworked by pressures from consumers demanding both improved environmental stewardship and better social conditions for workers. Their study reveals that pressures from lender and consumer organizations to reduce the negative socioecological impacts of production are leading to the environmental and social certification of beef, timber, and soybeans. Additional geographical research building on this conceptual and empirical foundation could further elucidate the nature of commodity networks and show how certification

programs rework inequality (e.g., Mutersbaugh, 2003; Tovar et al., 2005; Klooster, 2006).

Bassett's (2008, 2010) empirical research on cotton commodity chains linking West African agriculture to global markets provides further evidence that poverty and consumption are linked across space and scale (Moseley and Gray, 2008). Bassett explores how patterns of inequality across space and scale are shaped by the linkage of West African cotton farmers' incomes to market liberalization; relationships between producers, workers, and consumers; and interactions between ecological and social systems. He found that African cotton growers are relatively marginalized in negotiations over prices for seed cotton, fertilizers, and pesticides vis-à-vis ginning and marketing companies, as well as in dealings with cotton trading companies that set prices based on world markets. These negotiations with national cotton companies and the World Trade Organization are central to the setting of global cotton prices and so shape how and where returns to the crop are distributed among growers, ginners, and traders. Bassett's research also traces the relationship between currency values and farmers' incomes. For example, cotton trades globally in U.S. dollars, and yet currencies in Burkina Faso and Mali are pegged to the Euro. The recent devaluation of the dollar relative to the Euro thus reduced cotton farmers' returns on their internationally traded crops. In addition, Bassett's work reveals that U.S. cotton subsidies result in overproduction by U.S. producers, who generate 40 percent of global cotton production—thereby suppressing global cotton prices. As a result, farmers in West Africa, who do not have access to similar subsidies, face lower prices on international markets, resulting in lowered incomes (see also Friedberg, 2004, for a commodity chain analysis of French bean crops, and Gwynne, 2002, for a study of fruit exports from Chile).

Geographical research aimed at integrating economic, environmental, and social variables across place and scale can shed additional light on the impacts of market liberalization on inequality within states, at the local scale and across the globe. In particular, much could be gained from comparative case studies employing rigorous experimental frameworks that include common questions and metrics to facilitate aggregation and meta-analysis.

SUMMARY

An understanding of the causes and consequences of inequality requires consideration of geographical patterns and networks—whether economic, political, or environmental. Spatial analyses that take explicit account of place-to-place variations and scalar differences can be of particular value in the effort to elucidate the complex interactions between globalization and inequality.

9

How Are Geopolitical Shifts Influencing Peace and Stability?

Sweeping geopolitical changes have unfolded during the past two decades. The bipolar system of Cold War alliances has disintegrated, several states have broken up (the Soviet Union, Czechoslovakia, and Yugoslavia), new states have emerged (Eritrea, East Timor), and suprastate blocs have grown in significance, especially the European Union. Moreover, extrastate groups and institutions have challenged the state's geopolitical primacy (e.g., Lashkar-e-Taiba, Mercy Corps, the European Union),[1] even as new extensions of state power have undermined traditional sovereignty arrangements (e.g., the doctrine of preemptive warfare invoked to justify the 2003 invasion of Iraq). At the same time, the globalization of capital, labor, and finance is challenging the state as the prime actor in the international arena—albeit with mixed success.

These developments highlight the inadequacy of the long-standing tendency to view international relations as the product of a set of static spaces (i.e., countries) jockeying for position on the world stage (see generally Agnew, 1994; Taylor, 1994). Instead, a high priority for researchers is to understand the nature, significance, and relationships among multiple spaces of political relevance. Taking up this challenge requires exploring how power, interest groups, and territorial ideologies are spatially configured; how political patterns relate to environmental, ethnic, and other kinds of patterns; and how geopolitical conceptions reflect and shape social and environmental outcomes.

Research into such themes is important because the remaking of geopolitical space carries with it changing conceptions of "us" and "them" that influence how people view their collective interests. At the same time, the prospects for war and peace in different parts of the globe are fundamentally rooted in changing political-geographical arrangements and understandings. To what extent is "the Islamic World" a meaningful geopolitical construct, and how does that construct relate to other geopolitical constructs? Are new spaces of geopolitical significance emerging around access to water, oil, or other resources? To what extent are local or subnational ethnic divisions undermining traditional geopolitical arrangements? These types of questions hold significance for researchers seeking to elucidate key contemporary sociopolitical trends and for policy makers struggling to design arrangements that will promote peace and stability.

ROLE OF THE GEOGRAPHICAL SCIENCES

As an arena of inquiry focused on analyzing the organization of phenomena on the surface of Earth, the geographical sciences are necessarily central to the effort to examine the changing geopolitical scene. Their contribution is rooted in a concern with how and why political-territorial arrangements come into being, how

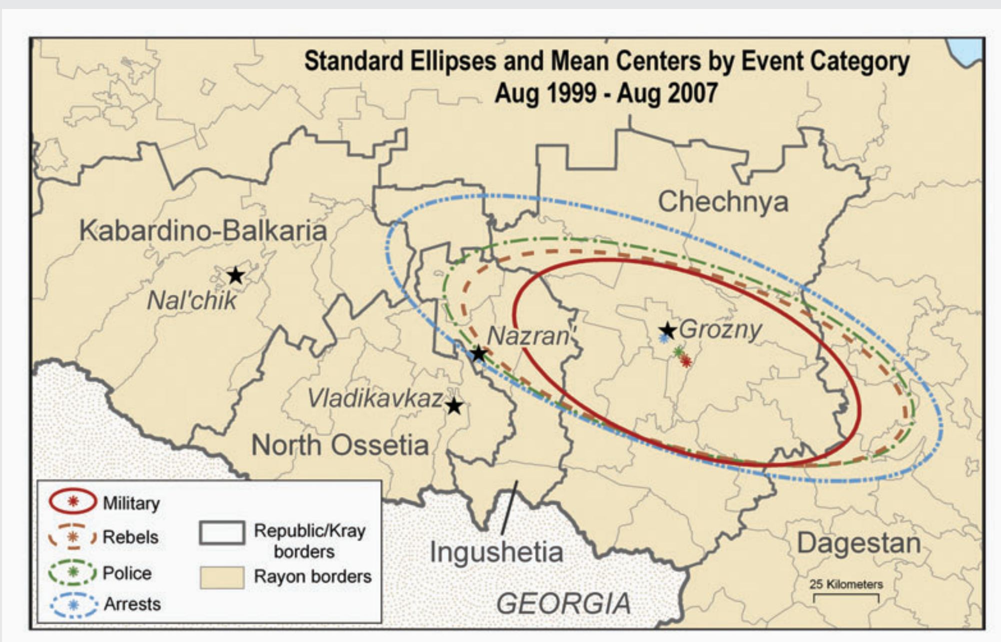
[1]Lashkar-e-Taiba is a South Asian militant organization that seeks to promote the Islamization of the region and to contest Indian authority over the Muslims of Kashmir. Mercy Corps is an extrastate nonprofit organization with headquarters in the United States and Europe that seeks to combat poverty, suffering, and oppression through community action projects. The European Union is the most far-reaching suprastate integration initiative in the world, encompassing 27 European countries.

they function given their geographical character, and how they relate to other economic, political, social, and environmental spaces (Gottmann, 1973; Sack, 1986; Paasi, 1996; Agnew, 2003). Researchers focusing on spatial orientation have also made significant contributions to the understanding of political developments, ranging from voting patterns (e.g., Shelley et al., 1996) to the distribution of armed conflicts (see Box 9.1).

In the geopolitical arena, work by geographical scientists has focused particularly on the cultural, political, and environmental impacts of boundaries (e.g., Rumley and Minghi, 1991; Newman and Paasi, 1998); the nature and implications of different geopolitical world views (e.g., Ó Tuathail, 1996; Dodds and Atkinson, 2000); and the relationship between territorial sources of authority and those that are not place specific (e.g., Flint, 2005a; Sparke, 2005). A study by Agnew and Min (2008) on the impacts of the U.S.-led surge in Iraq is suggestive of the value of probing the relationship between spaces of conflict and other geographical patterns. Using nighttime satellite images of Baghdad, Agnew and his colleagues were able to show that Sunni Arabs were driven out of many neighborhoods by militant Shiites in the lead-up to the surge. The research suggests that the reduction of conflict in the aftermath of the surge was not just a product of increased troop numbers, but of presurge ethnic cleansing and an associated spatial segregation of Sunnis and Shiites. Such

BOX 9.1
Spatial Distribution of Conflict

O'Loughlin, in collaboration with other researchers, has undertaken a series of studies on the spatial distribution of conflict that have provided insights into the causes and consequences of instability (e.g., O'Loughlin and Anselin, 1991; O'Loughlin and Raleigh, 2007). In one recent study O'Loughlin and Witmer (Forthcoming) compiled and mapped geocoded information on politically motivated violent events in the North Caucasus. Their research showed a steady spatial diffusion of military, rebel, and police engagements to the west and east from Chechnya's capital into North Ossetia and close to Makhachkala in Dagestan, but much less expansion to the north and south (see Figure). Their study revealed how conflict diffused from Chechnya to neighboring republics and provided insight into both the spatial strategies of participants and the types of areas that are more prone to instability.



Mean center and standard deviational ellipse of violent events in the North Caucasus, August 1999-August 2007 by type of event. SOURCE: O'Loughlin and Witmer (Forthcoming).

insights are of great value in efforts to understand the mix of forces that are shaping conflict and stability in different places.

The place-based approach that characterizes much work in the geographical sciences has also contributed to an understanding of the causes of conflict and peace. Viewed in general terms, many conflicts appear to be the result of a single economic, social, cultural, or environmental catalyst. However, myriad place-based studies have shown that violence is almost never a straightforward consequence of something such as resource scarcity (e.g., Peluso and Watts, 2001; Dalby, 2002; Le Billon, 2007). Instead, historical, political, and social processes operating at multiple scales affect how stakeholders attach value to the environment, contest claims, and struggle for outside support. Similarly, the potential for violent conflict among groups is often tied not only to economic or social inequalities, but also to localized geographical circumstances such as the distribution of groups and the availability of activity spaces that are beyond the reach of state authorities (e.g., Mikesell and Murphy, 1991; Fuller et al., 2000). Geographical perception matters as well, as made clear in White's (2000) study showing how spaces of particular symbolic significance can help explain patterns of ethnic conflict and compromise in southeastern Europe.

For all the insights that have come from investigations of the geographical dimensions of peace and conflict, there is much to be learned from research on the changing nature and significance of geopolitical ideas and arrangements. The following questions provide examples of some particularly useful lines of inquiry that speak to this theme.

RESEARCH SUBQUESTIONS

What types of boundary arrangements are particularly prone to instability, and why?

The combined forces of globalization and new forms of localism are challenging the traditional territorial powers of the state and fostering what some have termed a process of deterritorialization in the international arena. Nonetheless, bounded territories are still of enormous significance in human affairs (Elden, 2006; Newman, 2006), and in some instances boundaries are hardening (e.g., heightened controls at U.S. borders in recent years). The boundaries of some territories are widely accepted, but many are not. Interstate disagreements over boundaries are common, many ethnonationalist groups seek to alter existing territorial arrangements, and de facto internal territorial partitions are under great strain in many places (e.g., Jammu and Kashmir, Moldova, Bosnia). Understanding the potential volatility of different boundary arrangements requires consideration of how they are viewed; whose interests they serve; and how they relate to ethnic, economic, sociocultural, and environmental spaces at different scales (Herb and Kaplan, 1999).

The potential for geographical analysis to advance understanding of the nature and significance of boundaries is suggested by Jordan's (1993) analysis of the Vance-Owen plan for partitioning Bosnia during the civil war of the early 1990s. Jordan focused on the spatial relationship between the proposed ethnic regions in the Vance-Owen plan and the way people in Bosnia moved around and used space before the outbreak of hostilities (Figure 9.1). Data on preconflict commuting patterns allowed him to construct micro- and macro- "functional regions" (the lighter and darker hashed lines in Figure 9.1), which he then superimposed on the proposed partition map. The clear disconnect between the two patterns on the map provides insight into why the plan was so widely rejected. (Unfortunately, those crafting the plan did not undertake this kind of analysis before the plan was promulgated.)

Assessments of the relationship between territorial arrangements and patterns of ethnicity, environment, economy, and social interaction around contested boundaries could yield significant insights into the sources of conflict in many places. How have the establishment and adjustment of boundaries affected where people live, their activity patterns, and their senses of identity? Under what circumstances have shifting boundary arrangements produced more or less conflict? Circumstances are different from place to place, and part of the point of geographical analysis is to unravel how the particularities of individual circumstances produce certain outcomes. However, comparative geographical assessments of major contested boundaries around the world could yield fundamental insights into the relationships between territorial structures and social, cultural, and environmental patterns that are particularly

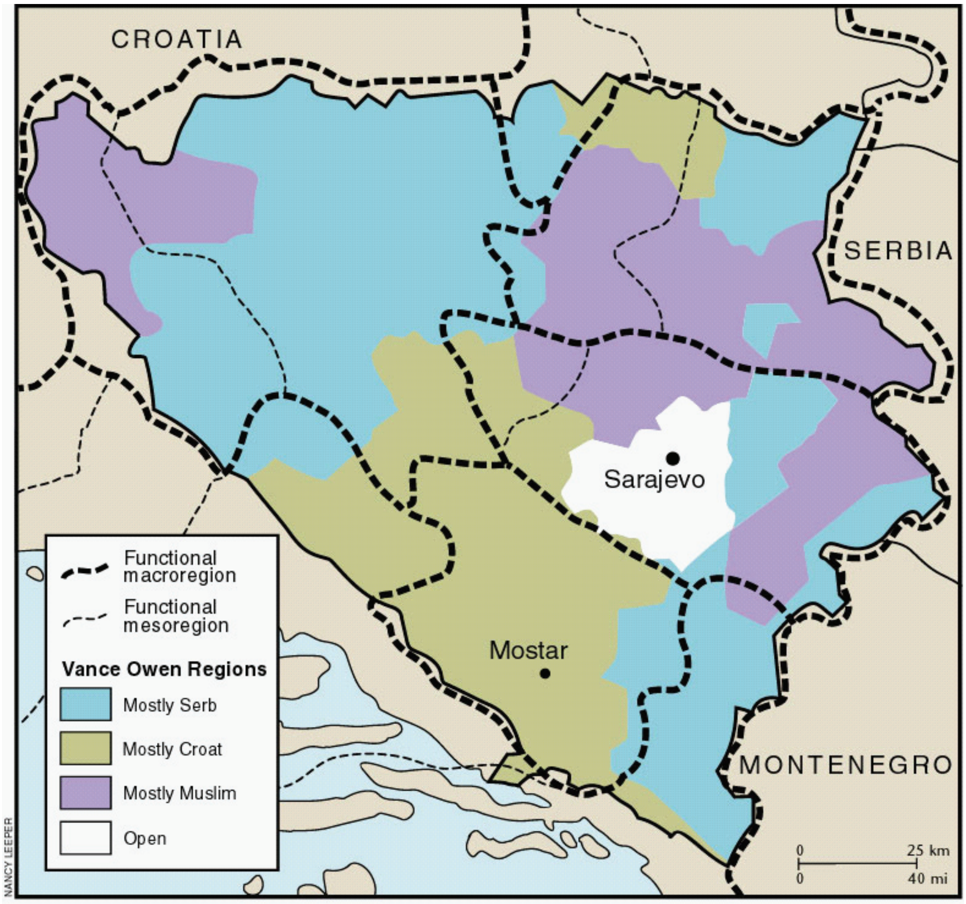


FIGURE 9.1 Map based on Jordan's (1993) study of the relationship between functional regions in Bosnia and the Vance-Owen partition plan. SOURCE: As modified by Alexander Murphy for *Geographical Approaches to Democratization: A Report to the National Science Foundation* (printed by the University of Oregon Press for the Geography and Regional Science Program, National Science Foundation).

destabilizing. Such assessments should focus not only on spatial patterns, but also on territorial conceptions as well. Past work has shown how dominant "senses of territory" are influenced by boundary arrangements and affect patterns of interstate and intergroup territorial conflict (e.g., Painter, 1995; Yiftachel, 2001; Murphy, 2005). What is needed is research that looks at both on-the-ground material circumstances and the senses of territory that are at play in different circumstances.

What are the implications of changing environmental circumstances and resource demands for geopolitical stability?

The environmental circumstances and resource endowments of different geopolitical entities have an impact on patterns of conflict and cooperation, power and political fragility. Yet these factors do not operate in isolation from other political, economic, and social forces (Clark, 2006b). As noted above, a significant body of contemporary work is aimed at highlighting the problems of attributing geopolitical circumstances solely to environmental or resource variables. Such work includes critiques of simplistic attempts to link conflict to resource scarcity (Fairhead, 2001), resource abundance (Watts, 2004), and common property resources (Turner, 2004). Although work in this vein has deepened understanding of the links between the environment and social stability, the combination of rapid environmental change and shifting resource demands opens a set of new research challenges that can only be met through analysis employing the approaches and techniques of the geographical sciences.

One particularly promising realm of research concerns the geopolitical impacts of sea-level rise in the wake of climate change. The relatively conservative predictions for the next century set forth in the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2007) point to a degree of sea-level rise in the 21st century that is likely to have significant

implications for many millions of coastal dwellers around the world, including those living in the United States (Figure 9.2). However, those implications are likely to be especially politically destabilizing in places with fragile governments, weak infrastructural coping capacities, and low standards of living. Assessments of the coping capacities of places with low-lying, densely populated coasts could provide useful insights into the geopolitical impacts of shifting coastlines (Heberger et al., 2009). Coastline changes will also alter the baselines that have been used to establish maritime boundaries. Determining where those changes are most likely to disrupt fragile agreements on ocean rights could help scholars and policy makers anticipate where problems are likely to arise and could promote understanding of the geography of conflict potential in the maritime arena.

It is important to recognize that environmental stresses are sometimes associated with cooperation, not just conflict (Wolf, 2002). Resource scarcity is a case in point. A body of work has yielded insights into the conditions that have produced cooperation in the face of resource competition at the local scale (e.g., Ostrom, 1990; Giordano, 2003). Others have examined how participatory resource management regimes may enable communities to prevent unproductive conflict (e.g., Martin, 2005). Still lacking, however, is much understanding of where and when such cooperation occurs at broader scales. Sneddon and Fox (2006) provide a useful starting point in their study of regional agreements on the sharing of water in the Mekong Basin. A systematic assessment of a variety of resource-sharing arrangements in other world regions could direct attention to the types of circumstances in which cooperation has been achieved and could pave the way to a better understanding of how general economic or political influences interact with local circumstances to promote stability.

Are territorial arrangements and ideas developing in ways that are consistent with the geopolitical visions of influential governmental and nongovernmental actors?

Ever since the publication of Samuel Huntington's (1996) controversial book on the *Clash of Civilizations*, debate has swirled around the geographical framework that underlies his analysis. Huntington's thesis is pre-

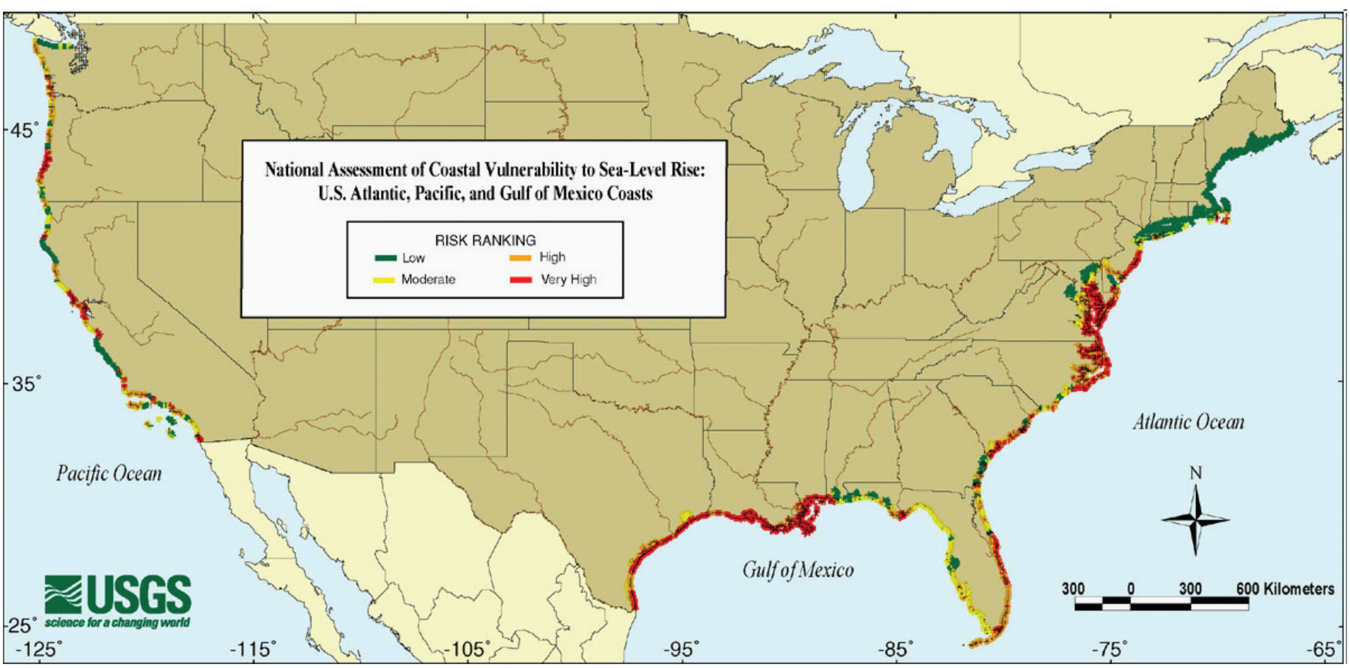


FIGURE 9.2 Focusing just on areas that are at "very high" risk from sea-level rise in one country is suggestive of the potential for rising sea levels to alter coastlines and disrupt the lives and livelihoods of people. SOURCE: USGS (2007).

mised on the rising significance of broad-scale religious identity as an organizing force in the contemporary world. Proponents of his thesis point to the growing salience of geopolitical movements with an explicitly religious agenda (most obviously Al-Qaeda). Critics argue that Huntington has ignored the long history of divisions within religious realms (see Bassin, 2007). The stakes in this debate are high because geopolitical framings can greatly influence policy and practice (Gregory, 2004).

Moving the debate forward requires consideration of the extent to which identity constructs based on generalized notions of religious or cultural continuities are challenging national and local loyalties. Even though the state system does not have deep historical roots in most parts of the world, states play an extraordinarily influential role in defining contemporary identity communities (Murphy, 1996; Wimmer, 2002). At the same time, in many places localized ethnic identities have a powerful grip on the collective imagination. To what extent do nationalist and localized ethnic identities—along with the institutions and arrangements that support them—represent a serious obstacle to the formation of the kinds of civilizational blocs posited by Huntington? Addressing this question requires empirical research focused on where, and under what circumstances, commitments to large-scale religious-cultural communities are superseding national and local identities, and where they are not. Of particular importance are intensive field studies focused on the institutional arrangements, spatial networks, and cultural practices that are shaping senses of place and identity in particular places and regions (see Carnegie, 2008, for a discussion of the utility of this kind of research in the effort to understand conflict). Those in the best position to undertake such studies are researchers with significant regional knowledge and linguistic skills who are interested in investigating geographical patterns and variations, both at the local scale (e.g., Secor, 2004; Mills, 2006) and at broader scales (e.g., Leitner, 2003).

The Huntington thesis is just one example of an influential geopolitical conception. Such conceptions are formulated by international organizations, think tanks, insurgency networks, and militaries; initiatives such as the National Intelligence Council's 2020 Project (NIC, 2004) shape decisions that can have sweeping social, economic, and environmental impacts. What do such initiatives include and ignore? What is the relationship between the visions set forth in them and underlying patterns of economic activity, cultural interaction, resource access, and territorial ideology? Which cultural, economic, or environmental circumstances are highlighted or obscured? Geographically grounded explorations of such questions can foster informed reflection on the often-unexamined geopolitical assumptions that guide policy making and scholarly analysis. The 2003 U.S. invasion of Iraq prompted an outpouring of scholarship on U.S.-based geopolitical visions (see e.g., Flint, 2005b; Bialasiewicz et al., 2007; Dalby, 2007), but much work remains to be done to assess the advantages and limitations of different geographical framings of this and other geopolitical issues (see Elden, 2009). It is also important to extend research beyond the major global powers of the 20th century. As Cutter et al. (2003), Flint (2003), and others make clear, to date relatively little attention has been paid to the assumptions and goals of emergent global actors, whether they be states (e.g., China or India), regional blocs (e.g., the European Union or the Association of Southeast Asian Nations), or extrastate religious and ethnic movements (e.g., Hezbollah or the Tibetan Autonomy Movement).

SUMMARY

Research by geographical scientists along the lines outlined above will deepen our understanding of some of the fundamental geopolitical forces shaping the security landscape of the 21st century. What is needed is a sustained effort to investigate the spatial character of geopolitical developments and conceptualizations and to analyze their relationship to key political-economic, environmental, and social patterns. Without studies in this vein, our understanding of key sources of geopolitical stability and instability will be impoverished.

10

How Might We Better Observe, Analyze, and Visualize a Changing World?

The observation, mapping, and representation of Earth's surface have been an integral part of geographical research since Ancient times, and these activities remain central to the modern geographical sciences. Maps of Earth's surface have provided an essential underpinning to a long series of research breakthroughs, such as the theory of continental drift and plate tectonics, our understanding of patterns of early human migration, inferences about the causes and transmission of disease, and global climatology. Today, the tasks of documenting, visualizing, and understanding the increasing rate of change that we observe on the planet's surface are far more complex than traditional mapmaking, demanding an increasingly elaborate network of Earth-observing satellites, ground-based observers and sensors, servers, and broadband communications, and the tools to analyze, model, and visualize. Collectively, these systems exploit decades of research by geographical scientists, represent an infrastructure investment that accounts for tens of billions of dollars annually, and address needs in all walks of life, from the work of scientists striving to understand and perhaps to predict, to the broader interests of the media and the general public, to the needs of emergency managers, planners, and a host of other professionals.

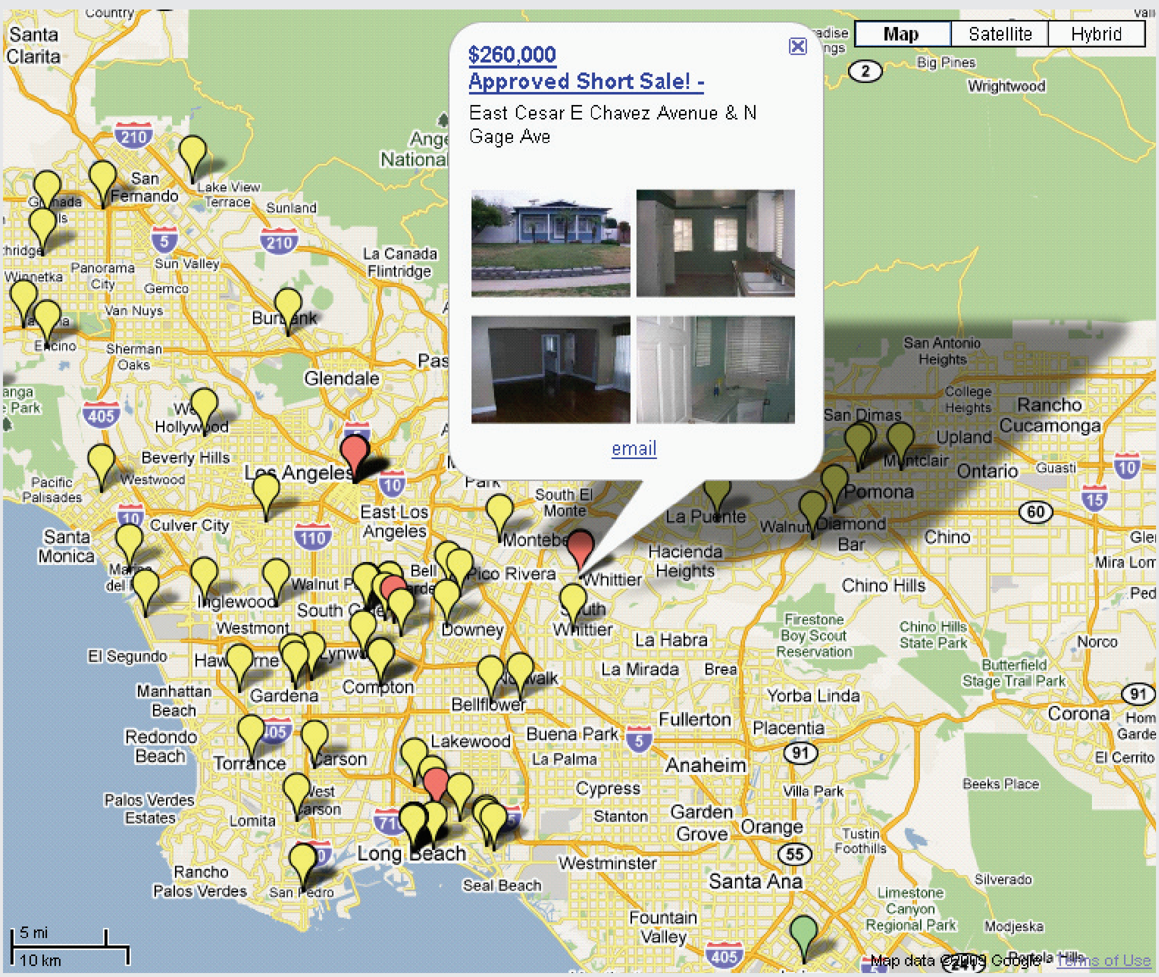
In recent years, the rate of development of new tools and data sources has been spectacular. Today most computer users are familiar with sites such as Google Earth, Microsoft's Virtual Earth, and other virtual globes that allow them to visualize the current physical appearance of Earth's surface using imagery obtained from satellites, aircraft, or specially equipped vehicles. Many people make daily use of navigation systems, and of the host of Web-based services that now link diverse sources of data based on geographical location (Box 10.1). However, despite these developments, the geographical tools, knowledge, and understanding with which humanity faces the uncertainties of the 21st century are inadequate in many respects. Surprisingly, conventional mapmaking has been in decline worldwide for several decades (Estes and Mooneyhan, 1994), and many basic maps, including those covering the United States, are no longer updated. Although Web-based virtual globes display stunningly detailed images of how the geographical world looks, they provide little sense of how the world is changing, how it will look in the future, how certain or uncertain we may be about future states, and how the world works as an interconnected system. The general public makes use of these technologies to obtain driving directions and to look at recent events around the world, but gains very little understanding of the many problems that humanity faces, and the options available for dealing with them that have been discussed in previous chapters. The methods of analysis that search for pattern, anomaly, and correlation in geographical information reflect the needs of an earlier, slowly changing world and its somewhat leisurely pace of investigation, rather than the rapidly changing planet of the new century, and its need for quick, science-based response.

Geographical data and tools are now essential for the full range of research disciplines that study the Earth's surface and near surface, from the social sciences

BOX 10.1
Linking Information Sources with Geographical Location

Geographical location is now widely used on the Web as a means to link two or more existing sources of information to create a new service, providing information that would otherwise have been unavailable. These combined services are commonly known as mashups, from a term used in the recording industry to refer to music created by combining previously independent tracks. Together they form what is often termed the GeoWeb, a spider's web of services held together through the use of geographical location, whether expressed as latitude/longitude, place name, street address, or any other convenient system of georeferencing.

As an example, houses listed for sale on Craigslist (www.craigslist.com) are first analyzed by a mashup service to obtain their street addresses, which are then converted to latitude/longitude using a Web-based geocoding service (see Figure). The mashup service, www.housingmaps.com, combines these coordinates with a mapping service (Google Maps, maps.google.com) to provide detailed and useful maps of where houses are listed for sale, along with other information about the house—something that neither Craigslist nor Google Maps is capable of providing on its own.



A map of houses currently listed for sale in the $150,000-300,000 price range by Craigslist for part of Los Angeles. This www.housingmaps.com mashup combines Craigslist data with Google Maps. SOURCE: www.housingmaps.com.

such as criminology or political science to the environmental sciences such as climatology or ecology. They are an absolute necessity if scientific understanding is to be translated into effective evidence-based and place-based policy, and if the average citizen is to become fully informed and engaged in discussions about potential uses and abuses of geographical technologies.

Earth observing satellites provide powerful observations of the physical parameters that characterize the Earth system, including sea-surface temperatures, rainfall, and land cover. Geographical scientists have benefited from the massive investments that have been made not only by U.S. government agencies, but also by the private sector and by agencies in other countries. They have discovered effective means of turning raw sensor measurements into characterizations of the land surface, and have applied these in numerous ways, many of them discussed in other chapters of this report (e.g., Chapters 2, 3, and 4). However, many of the social aspects of the Earth system cannot be observed or measured from above, and understanding of them must therefore rely on people's willingness to divulge sensitive information about themselves in programs such as the U.S. Census.

ROLE OF THE GEOGRAPHICAL SCIENCES

The activity of describing and drawing the world—the literal root of the term geography—has changed dramatically over the centuries. An editorial in *Nature* (Editorial, 2008) went so far as to argue that our museum collections are full of specimens collected at vaguely recorded locations (Guo et al., 2008), but there is now no longer any excuse for not recording the location of any scientific observation made of phenomena on or near Earth's surface. For many researchers much of the science of cartography, or the drawing of maps that accurately convey knowledge, has been encapsulated in a series of default options in software. Access to the products of remote sensing, once a task requiring a great deal of technical knowledge, is now reduced for many users to the manipulation of the simple user interface of a desktop or laptop computer, or even a hand-held PDA (personal digital assistant).

However, although it has undoubtedly become easier to work with geographical data and tools, we should not confuse the act of "describing and drawing" phenomena with the geographical knowledge and understanding that are embedded in today's tools and data acquisition systems, or with the processes of reasoning and inference that translate raw observations into scientific knowledge and ultimately into improved decisions. Even though it is possible to make a decent-looking and informative map by doing no more than accepting the default options of a software package, the science of cartography is still an active field. Remote sensing, a workhorse of modern geographical data acquisition, continues to advance, making use of new kinds of sensors that exploit different parts of the electromagnetic spectrum, access a broader range of acoustic frequencies in the case of marine remote sensing, and achieve finer levels of spatial, temporal, or spectral resolution, and each new development opens opportunities for research into additional applications in the geographical sciences.

None of these developments, however, has in any way reduced the importance of expertise in reasoning and inference, and it is clearly in this area that the role of the geographical scientist is most critical (Longley et al., 2005). No one would suggest, for example, that technology has in any way reduced the need for expert pedologists, both as creators of knowledge about soils and as interpreters of that knowledge to users, even though that knowledge may be expressed through the simple medium of a map. Similarly the expertise of the cultural geographer in observing and interpreting the human landscape can never be encapsulated in software. Geographical scientists understand the nature of particular classes of phenomena through their training and knowledge of the literature. They are aware of the importance of spatial concepts such as scale, location, place, and interaction (Gersmehl, 2005); are familiar with their underlying theories and the pitfalls associated with each; and are capable of making effective use of the geographical data and tools at their disposal to augment the sum of human knowledge about the geographical landscape, while remaining cognizant of the inevitable uncertainty associated with that knowledge.

Past investments in research into geographical data and tools have produced dramatic progress. The stunning zooms and pans of the virtual globes rely on fundamental research by geographical scientists into ways of capturing the curved surface of the planet in digital form, a research area known as discrete global

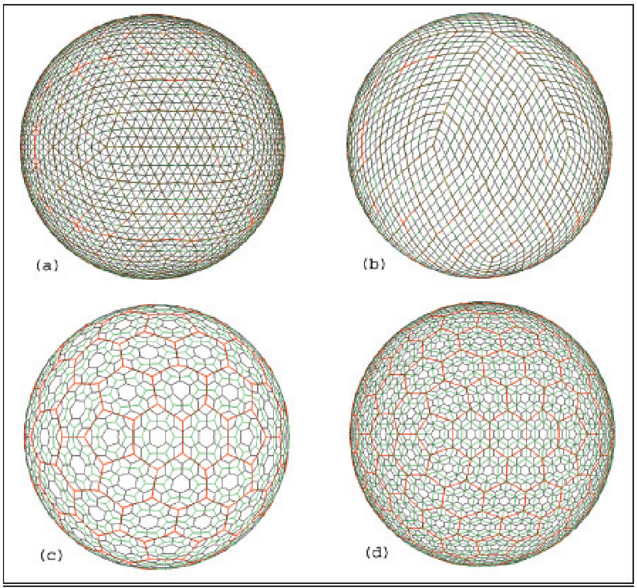


FIGURE 10.1 Illustrations of icosahedron-based discrete global grids at several resolutions. SOURCE: Sahr et al. (2003).

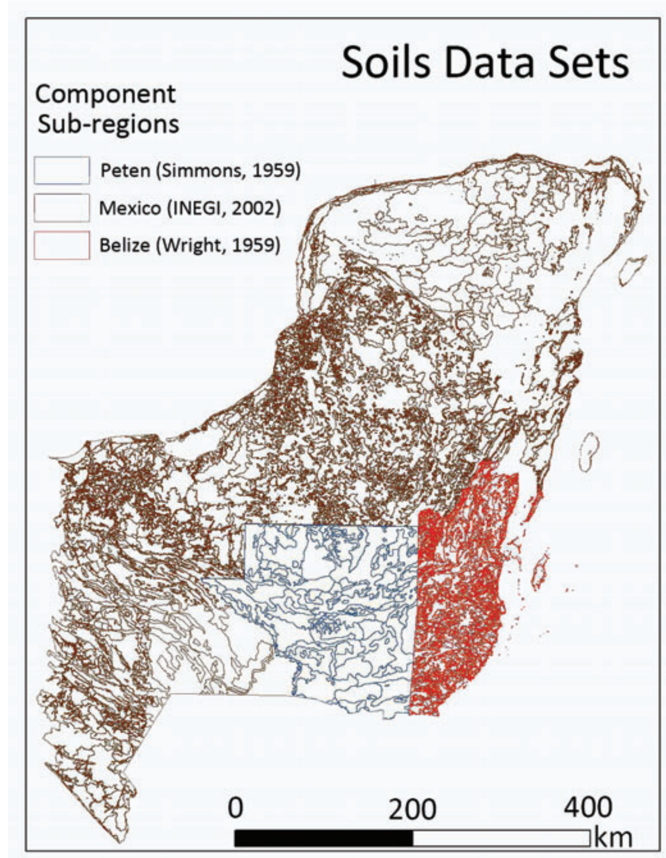


FIGURE 10.2 Soil map of the Yucatan Peninsula compiled from datasets from three different countries: Mexico (brown), Belize (red), and Guatemala (blue). For clarity, only the boundaries between areas of homogeneous soil are shown. Note the different densities of boundaries, indicating differences between national standards and practices (and also state standards in Mexico). SOURCE: Sifuentes (2005).

grids or geodesic grids (Figure 10.1), and on research in computer graphics into managing the level of detail in various parts of the visual field (level-of-detail management). Research on geographical semantics is making it possible to integrate data across national boundaries despite differences in mapping practice, terminology, classification schemes, and data formats (Figure 10.2; Goodchild et al., 1999). Much more is known now about the sources of uncertainty in geographical data, about visualizing its importance, and about modeling its impact on the results of analysis (Zhang and Goodchild, 2002). New techniques of geovisualization allow geographical data to be displayed simultaneously from many different perspectives, leading to new insights and the generation of new hypotheses (Figure 10.3). Significant advances have been made recently by geographical scientists in areas such as visualizing dynamic, multidimensional phenomena (Dykes et al., 2005; Slocum, 2009) and adapting mapmaking to the needs of the visually impaired (Golledge et al., 2005; Rice et al., 2005). All of these make use of digital technology, but require expertise not only in computer science but also in the disciplines that are intimately concerned with phenomena on Earth's surface. There is no doubt that progress will be at least as dramatic in the future, as geographical scientists explore the opportunities created by advances in mainstream information technology, by new sensors, and by new ways of thinking about the role of the geographical perspective as a cross-cutting theme in science. The following questions illustrate lines of research that would be particularly productive to advance this topic.

RESEARCH SUBQUESTIONS

How will new geographical knowledge be acquired and shared?

Many of the more recent developments in geographical technology relate to data gathering. Satellite remote sensing (Jensen, 2007), which dates from the

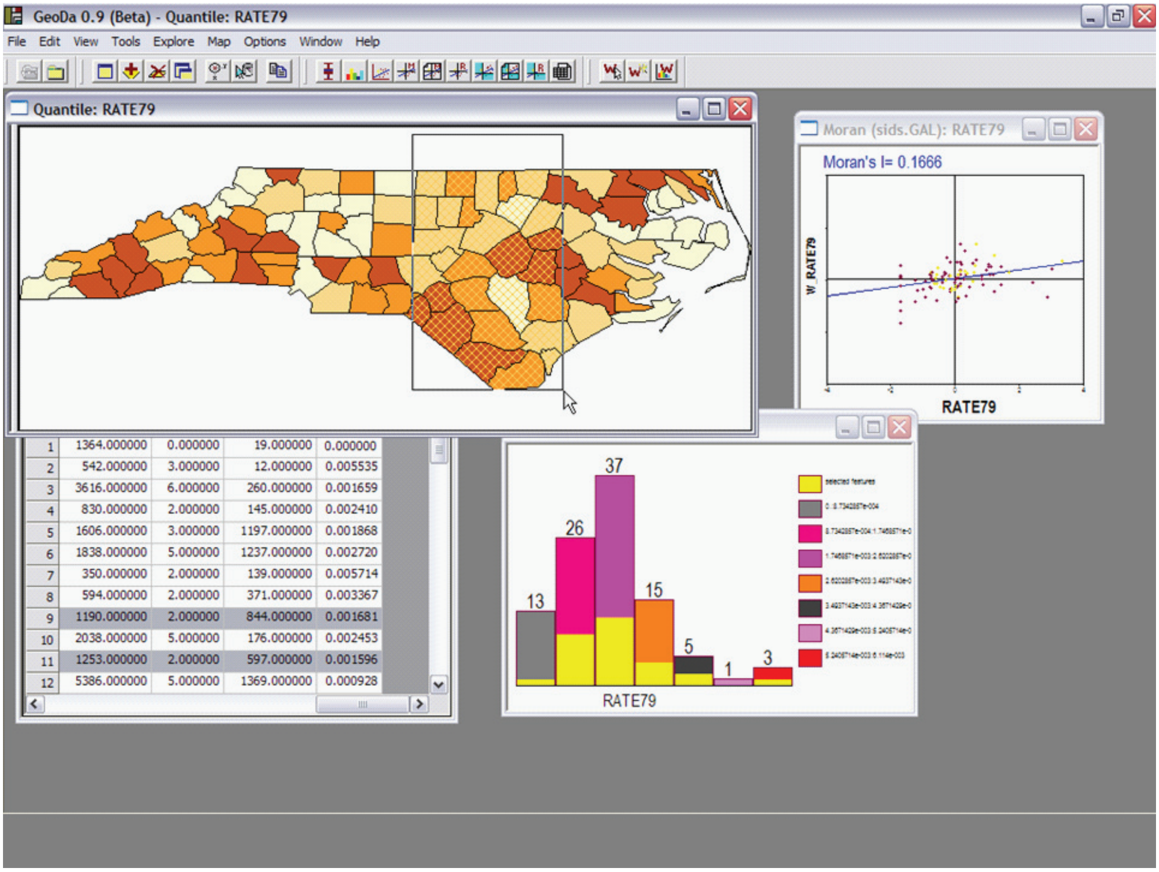


FIGURE 10.3 Screenshot from the software package GeoDa, developed for the exploration and analysis of geographical data and available free for download from the GeoDa Center at Arizona State University, geodacenter.asu.edu/. This example shows data on the rate of sudden infant death syndrome by North Carolina county from four different perspectives: map (upper left; darkest colors depict the highest rates), table (lower left), histogram (lower right); and in the upper right, a scatterplot of each county's rate against the average of its neighbors, a plot that allows the easy identification of counties with anomalous rates that stand out from their neighbors. The rectangle, which can be maneuvered by the user, results in the highlighting of contained counties in every window. SOURCE: GeoDa 0.9 (Beta).

spy satellites of the Cold War, has evolved into a multinational enterprise producing terabytes of data per day on various characteristics of Earth's surface, at spatial resolutions that now extend to the submeter level. Passive sensors gather radiation from the surface in visible and near-visible wavelengths, while active sensors "ping" the surface using radar, light, and microwave radiation to create accurate maps of topography, of land cover and snow, and of the immediate subsurface. Satellite-based remote sensing also provides needed inputs for models of the atmosphere that lead to accurate forecasts of temperature, rainfall, and extreme events; for monitoring of sea-surface temperature; and for a wide range of other parameters. Similarly, acoustic remote sensing, which dates from the naval vessels of World War II, has grown exponentially in importance, given the need for detailed mapping and analysis of water-column properties for climate change studies, of the related need for ocean fisheries habitat restoration and conservation, and for seafloor or subseafloor energy extraction and tsunami modeling. The geographical sciences have been central to the design of these systems; to the techniques used to interpret imagery to identify crop types, land-cover types, benthic habitat types, and biomass production; and to the research that emerges from the detailed analysis of the results (Jensen, 2005, 2007; Lillesand et al., 2008). They will continue to do so as the science of remote sensing advances in the coming years. Finer spatial resolution, more frequent overpasses, finer spectral resolution to allow more accu-

rate identification of cover and habitat types, more reliable tools for classification, faster processing, and more effective systems for distributing data will all work to enhance the benefits of remote sensing to science, to the development of public policy, and to the work of a myriad of agencies and communities.

Recently, there has been much interest in ground-based remote sensing, using networks of fixed, autonomous sensors capable of gathering useful information on properties of the environment. Sensor networks now provide a steady flow of information on worldwide sea levels, allowing scientists to test predictions of sea-level rise; they provide a cheap and dense network of ground-based weather measurements; and they provide a steady flow of useful information on traffic densities on roads.

However, there are obvious limits to what can be observed, identified, and measured from remote sensors, whether in space, on the ground, or in the ocean. People use place names, distinctive landmarks, and addresses to describe locations, but maps of these are created by humans on the ground. Data on demographics, socioeconomic status, and all of the wealth of information created by censuses, surveys, and other mechanisms for gathering social data are available only from people, and only by expensive processes of official data gathering. It is important that researchers find ways of sustaining these processes despite their cost and what appears to be an increasing unwillingness of some members of the public to participate.

An active and promising line of research by geographical scientists focuses on the use of unconventional sources to elicit or infer detailed social information. For example, Longley developed powerful techniques for deriving spatially detailed social data using personal names (Longley et al., 2007; Gibin et al., 2008), while the field of geodemographics (Harris et al., 2005) mines spatially disaggregated social statistics to sort neighborhoods into distinct social types. Recently, a range of projects has focused on eliciting and compiling detailed geographical data from the general public, a topic discussed in greater detail in Chapter 11. In all of these cases research is needed to understand the quality and usefulness of the results and to protect the interests of the providers in preserving confidentiality.

Underlying all of these approaches to data acquisition is the problem of sustaining long-term programs that can yield useful longitudinal data. All too often geographical datasets are no more than snapshots, obtained at a few times over a short interval. Changing technology, lack of interest, and the short-sighted nature of many programs present a major obstacle to any concerted effort to build lengthy time series that can support analysis of change. We run a real danger that, in the not too distant future, much of what we now know about the planet through our current programs of remote sensing will be lost because of a lack of both the resources and the organizations needed for long-term preservation. Research is needed to identify robust approaches to preservation, to ensure easy and reliable access by the researchers of the future.

What techniques will be needed to visualize Earth futures?

In an address written for the opening of the California Science Center in Los Angeles in early 1998, Vice President Al Gore expanded on an idea he had first proposed in 1993 (Gore, 1993) for an immersive environment he termed Digital Earth, which would let its users explore a visual representation of the planet. The idea of a digital replica of Earth, or mirror world, also appears in Neal Stephenson's novel *Snowcrash*, published in 1992.

Although the technology of 1998, with its limited Internet connectivity and lack of advanced three-dimensional graphics, made this concept seem almost impossibly futuristic, by 2005 the average personal computer had sufficient power in visual display, and a sufficient number of households were connected by broadband communications, to make Gore's basic vision a reality for millions of people. In that year Google acquired, rebranded, and substantially enhanced a 4-year-old software product called Earthviewer, and launched the result as Google Earth, in many ways an implementation of what Gore had described 7 years earlier. Several other virtual globes have followed, and more than 300 million copies of the Google Earth client software have been downloaded. Most users are content to zoom from global to local scales to see their own houses and neighborhoods, but the publication of the Google Earth application programming interface has allowed users to create literally hundreds of thousands of applications. Google Earth has been

described as "the democratization of GIS [geographic information systems]" (Butler, 2006) because it has allowed millions of users to become familiar with some of GIS's very basic operations.

However, although virtual globes allow us to see a rough approximation of how the world looks (at the time the base imagery was acquired), Gore goes on to describe how a Digital Earth could be used to explore both the past and the future of the planet. Our ability to simulate the future relies on our understanding of the processes, both social and environmental, that shape the planet, and to do so at apparently increasing rates. Google Earth now has the ability to display a sequence of snapshots representing the development of some phenomena through time, and many mashups have been created to show historical data, but the ability to visualize future scenarios by exploiting our understanding of processes remains essentially futuristic. Enhancing forward-looking visualizations will require research in many disciplines (Craglia et al., 2008), including the geographical sciences, on topics such as the following:

- Methods to use the spatial structure of virtual globes (discrete global grids) as the basis for a range of simulation models;
- Methods of visualization that go beyond the current emphasis on rendering a realistic approximation of Earth's surface appearance, and include properties that are abstract or nonvisual in nature, such as personal income, gross domestic product, or rainfall;
- Standards and mechanisms that allow a user to search not only for data, but also for simulation models, and to implement them in a virtual globe environment;
- Tools that allow models of a wide range of processes, from environmental to social, to be represented using a common and reusable set of software primitives;
- Methods for downscaling predictions to the local level, so they can be made meaningful in a local context; and
- Ways of enhancing understanding of the uncertainty associated with simulations of process, and of how that uncertainty can be displayed on a virtual globe and communicated to the user.

Today, detailed forecasts of global climate change are readily available in the scientific community, but the high level of technical and domain expertise needed to access them limits their value. Policy makers and individual citizens are far more likely to respond to such forecasts when they can see their implications locally. The idea of bringing the global message home, of localizing the global, was very much part of Gore's original vision for Digital Earth—and far beyond what we can do today.

How can geographical tools be adapted to a world that needs just-in-time answers?

Because of the legacy of mapping relatively static phenomena, our methods of analysis are similarly geared to so-called cross-sectional data, or data of spatial distributions at one point in time. This limitation is exacerbated by the tendency for many social data-gathering exercises, such as the U.S. Census, to take place at fixed intervals. Remotely sensed images have also provided timed snapshots, although the effective frequency of overpasses has been improving recently as more satellites are launched, allowing the recovery effort following the Wenchuan earthquake in China in May 2008, for example, to make use of images collected from dozens of satellite sensors. Another reason for the paucity of lengthy time series has been the difficulty of maintaining the flow of public resources needed to keep large-scale, expensive government data-gathering programs in operation decade after decade.

As change accelerates and as sensor networks begin to provide densely sampled data in both space and time, we will need to add rapidly to our collection of spatio-temporal techniques of analysis. At this time, we know little about how to analyze and mine the increasing supply of data resulting from the tracking of vehicles, people, and animals (Miller and Han, 2001). We know little about how to assess the significance of an apparent change on Earth's surface detected by remote sensing. We need a comprehensive battery of easy-to-use models to simulate a range of social and environmental processes, and to investigate the footprints they leave on Earth's surface.

Even more urgent is the need for methods that can continuously monitor the stream of data coming from our acquisition systems, searching constantly for

anomalies and novel patterns, and initiating appropriate investigations. Such real-time analysis of medical diagnoses by primary care physicians, for example, could provide early warning of disease outbreaks and health hazards. Data coming from individuals could be used to provide early assessments of the damage from disasters, and could speed the initiation of response. Spatial decision-support systems based on real-time streams of data could provide new levels of effectiveness in the management of numerous social and environmental problems.

SUMMARY

Advances in technology in the contemporary area present new opportunities and challenges for the age-old task of observing, mapping, and representing Earth's changing geographical character. Pursuit of the illustrative research questions presented in this chapter will enable the geographical sciences to collect, analyze, and share information in ways that are critical to the multidisciplinary task of understanding and assessing the human and environmental processes that are shaping the future of the planet.

11

What Are the Societal Implications of Citizen Mapping and Mapping Citizens?

The popularity of Web mapping sites such as Google Maps, Google Earth, and Microsoft Virtual Earth has exploded in recent years. Particularly in wealthier parts of the world, these sites have become a central part of daily life (the "next utility") as they are used to navigate to places of work, pleasure, and commerce, and to allow citizens to increase their knowledge of the world. Not only do people want to receive information from these sites; they increasingly want to share it as well. Sites, such as Wikimapia.org, OpenStreetMap.org, MapAction.org, and Flickr.com are empowering millions of citizens to create a global patchwork of geographical information. This information is already serving society in many ways—assisting in local tourism and community planning, disaster response (e.g., citizen maps of Southern California fires), humanitarian aid, habitat restoration, public health monitoring, and personal assessments of environmental impacts. This citizen mapping "workforce" is largely untrained, under no authority, and the mapping is often done for no obvious reward (Goodchild, 2007).

Goodchild (2007) terms this recent phenomenon "volunteered geographic information" (VGI), wherein a private citizen participates in the creation, assembly, and dissemination of geographical information on the Web. The information is "volunteered" primarily by adding a geographical identifier (known also as a geotag) to a Wikipedia article, photograph, or video, or by adding one's own geographical data to an interactive, Web-based map, often by marking locations of certain features that are of importance, places where various events have occurred, or places where an individual has been or would like to go (Figure 11.1). For those with more advanced computing skills, Google Earth and other virtual globes are providing ways for citizen mappers (known also as neogeographers) to develop their own mapping applications, such as geoGreeting, which create greeting messages in Google Maps spelled out in satellite images of real buildings from all over the world that happen to be shaped as letters when viewed from above. VGI can be a boon, for example, to international development and humanitarian relief organizations, which can supply these organizations with the most up-to-date detailed data (Figure 11.2).

The power of such Web sites to increase the efficiency, pleasure, and safety of our lives is becoming increasingly apparent. However, the issue of individual privacy has arisen just as quickly as the technologies themselves. Privacy is about limiting access to facts about an individual, including gender, marital status, income, and social security number, in order to protect against intrusion, appropriation, or breach of confidence. The issue of privacy is heightened when locational information is involved. Most people do not expect ultimate privacy while at their places of work, but they expect it in their homes. Location can also present privacy concerns in a dynamic sense, both directly ("I don't want people to know my current location in space and time") and indirectly ("I don't want certain things associated with me *because* of my current location in space and time, such as my presence at an adult video store") (Curry, 1998; Armstrong and Ruggles, 2005; Bertino et al., 2008).

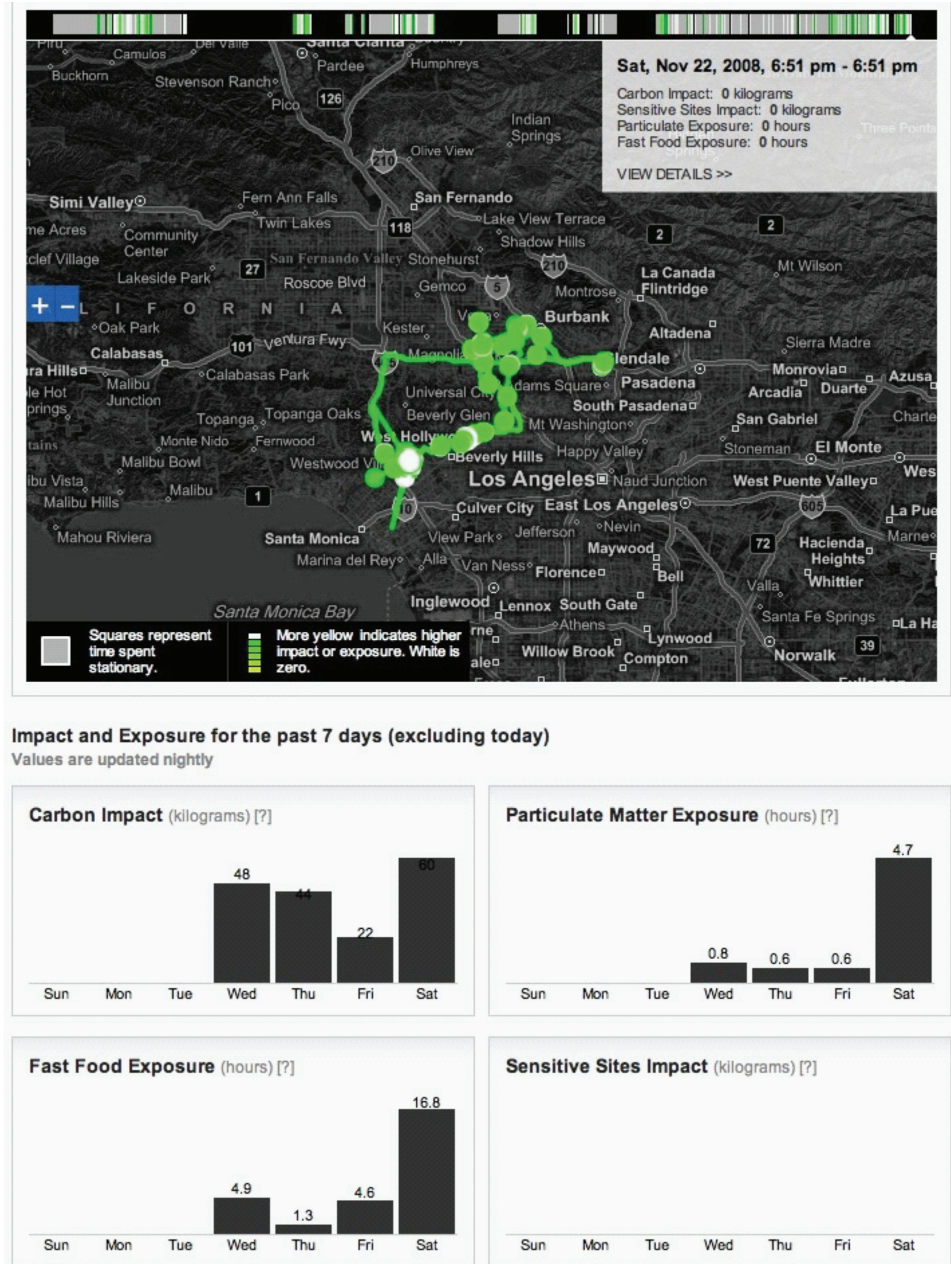


FIGURE 11.1 Example of a VGI project from the University of California, Los Angeles Center for Embedded Networked Sensing, where private citizens use their mobile phones to explore and share the impact of the local environment on their lives and vice versa (e.g., Cuff et al., 2008). The map and graphs show demonstration outputs from the Personal Environmental Impact Report, an online service that interacts with a user's mobile phone to provide an environmental "scorecard" that tracks possible exposure to carbon emissions, fast food, and particulates, as well as impact on sensitive sites throughout the Los Angeles metropolitan area. In this sense, the citizens themselves become the environmental sensors. The service is accompanied by a privacy policy for participants that explains the risks of collecting and sharing location information and how data and information are being controlled. SOURCE: peir.cens.ucla.edu (accessed January 20, 2010).

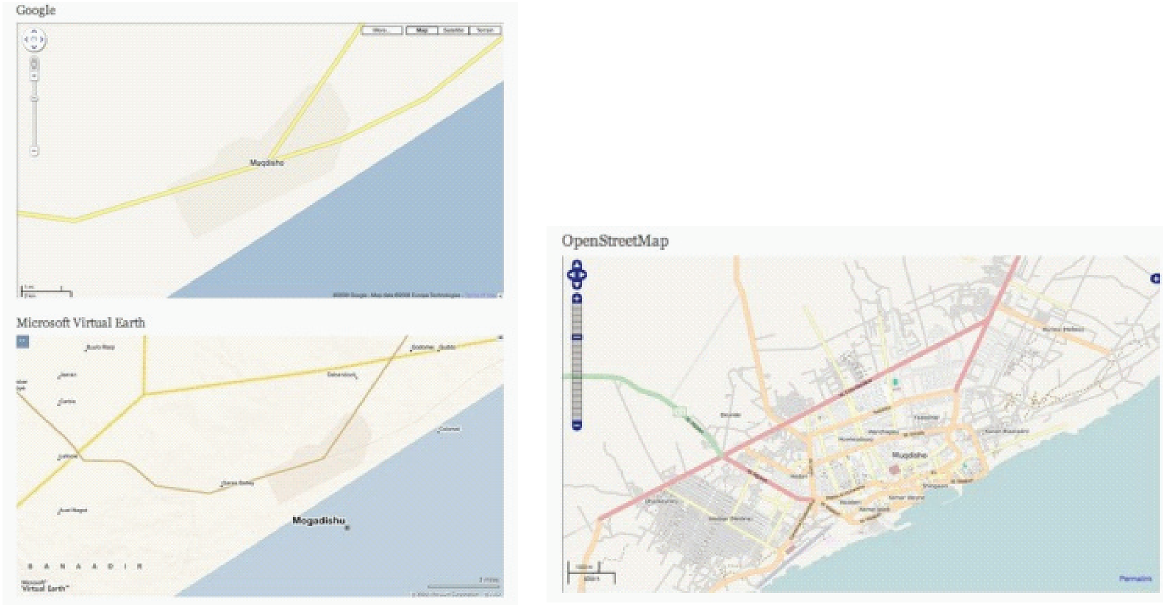


FIGURE 11.2 The map on the left shows part of the street network in Mogadishu, Somalia, available in Google Earth (top) and Microsoft Virtual Earth (bottom). The map on the right showing the same region, but with streets supplied by VGI in OpenStreetMap.org, provides information of considerable use to international development and humanitarian relief organizations. SOURCE: www.developmentseed.org/tags/mapping (accessed January 20, 2010).

THE ROLE OF THE GEOGRAPHICAL SCIENCES

Most citizen mapping involves the use of the Internet. Some view the Internet as a technology that is abolishing the significance of geographical location and distance (e.g., Cairncross, 1997), but there is much evidence to the contrary. As noted in *The Economist* (2003):

> It was naive to imagine that the global reach of the Internet would make geography irrelevant. Wireline and wireless technologies have bound the virtual and physical worlds closer than ever. . . . Actually, geography is far from dead. Although it is often helpful to think of the Internet as a parallel digital universe, or an omnipresent "cloud," its users live in the real world where limitations of geography still apply. And these limitations extend online. Finding information relevant to a particular place, or the location associated with a specific piece of information, is not always easy.

It follows that geographical context is relevant to any discussion of the nature and implications of VGI and its enabling technologies. VGI is often made possible through the use of geographically enabled "smartphones," personal digital assistants or PDAs (i.e., handheld computers), digital cameras, and vehicle navigation systems. These devices are equipped with ready-made maps and Global Positioning System receivers, further empowered by a location-based service (LBS). LBS is an information service provided by a device that knows *where* it is and then uses that knowledge to select, transform, and *modify* the information that it returns to the user. Hence the device can supply driving or walking directions to businesses, restaurants, and automated teller machines; find other users in close proximity; or even send alerts, such as when a user is approaching a traffic jam or accident. Peter Batty (a former chief technology officer of two leading geographic information system [GIS] companies) has recently introduced *whereyougonnabe.com*, which takes this kind of networking one step further by allowing users to tell their friends where and when they plan to be located in the future.

There is growing concern that the proliferation of technologies and the production of detailed, micro-level spatial data are outpacing our ability to protect information about individuals. The same techniques that allow Web users to create mashups by linking infor-

mation around common geographical locations also allow government agencies to build massive databases on individuals and their behaviors (e.g., NRC, 2008a) and make it possible for the private sector to keep track of a wealth of personal information. The practitioners of the emerging field of "collective intelligence" acknowledge that, if misused, locational information on individuals "could create an Orwellian future on a level Big Brother could only dream of" (Markoff, 2008). The geographical sciences are of central importance to this challenge because, as noted by the NRC Committee on Confidentiality Issues Arising from the Integration of Remotely Sensed and Self-Identifying Data (NRC, 2007b): "precise information about spatial location is almost perfectly identifying: if one knows where someone lives, one is likely to know the person's identity." The social issues raised by these tools are more urgent today than two decades ago, and there is every indication that the urgency will grow in the future.

The geographical sciences are central to understanding the nature and implication of new forms of data acquisition. Geographical scientists have the background and training to bring to bear language, guiding principles, and theoretical constructs that are relevant to locational and mapping technologies. They offer research methods that can facilitate the exploration, analysis, synthesis, and presentation of data about citizen mapping activities and their social implications. The concern of geographical scientists with place and context is particularly important, as the study of citizen mapping and locational privacy is not just about acquiring and using locational data. It is about understanding how data are used and viewed in particular places, and by particular communities. Geographical scientists wonder not only about the "where" of the present, but the implications of "where" for the future, and how spatial behaviors will change under the circumstances of traffic congestion, crisis (emergency evacuation from natural disaster, terrorist attack; e.g., Torrens, 2007), or even mass euphoria (musical concerts or a political rally). Bringing these concerns to bear on citizen mapping initiatives and locational data collection is essential to the effort to understand the social implications of geographical practices.

The responsibility of the geographical sciences to confront this issue becomes clear when one considers that geographical research itself may infringe upon the personal privacy rights of individuals. Box 11.1 describes one present-day example. The following research questions provide examples of issues that would be particularly productive to investigate.

BOX 11.1
Tracking Residents in Bath, England

'There's a storm brewing in [the English town of] Bath. Today's *Guardian* newspaper reports that residents are being tracked without their knowledge. The tracking is part of a University of Bath project that's called Cityware [a research collaboration of computer scientists and psychologists]. It's designed to study how people move around cities. Here's how it works. Cityware researchers have installed scanners at secret locations around Bath. Those scanners capture bluetooth radio signals. Bluetooth is a short-range wireless technology. It's found in mobile phones, laptops, even digital cameras. Now if somebody in Bath moves by a scanner with his or her bluetooth device turned on, then Cityware can pinpoint that person's whereabouts. The results are stored in a database. Researchers and city officials contend that they cannot identify anyone personally from the data collected, but the scanners don't let Bluetooth users KNOW that they are being watched, and some have called 'foul. . . .' [transcripted from the radio broadcast Public Radio International's *The World,* as broadcast on July 21, 2008, available also at www.theworld.org/?q=node/19600].

The researchers of this study maintain that the purpose of Cityware is not to track individuals, but to study the aggregate behavior of city dwellers as a whole, while also allowing those individuals to find their way around the city, participate in interactive citywide games and cultural activities, and access a host of information services while working, socializing, or relaxing (Lewis, 2008). The human rights "watchdog" group Privacy International has countered that "it would not take much adjustment to make this [Cityware] system an ubiquitous surveillance infrastructure over which we have no control" (Lewis, 2008).

RESEARCH SUBQUESTIONS

What are the characteristics of the producers of VGI and how should we evaluate the content and quality of what they have produced?

Producers of VGI are themselves subjects of much needed research (e.g., who volunteers and why, what are their geographical and social characteristics, what kind of locational information are they interested in volunteering?). Initial studies have shown that people

volunteer information in the belief that it will be open, accessible, and free, and may even be of significant help. Some are also motivated by self-promotion, the desire to fill in gaps in data, or merely to connect easily to friends, relatives, and colleagues (Goodchild, 2008). Geographical methods for exploration, analysis, synthesis, and classification of spatial data (e.g., multiple-criteria evaluation methods in the context of decision-support systems as developed by Jankowski et al. [2008], as well as various landscape visualization techniques and participatory three-dimensional models) are needed to shed light on who is involved in VGI and what they are doing. A study that mapped participation and correlated it with multiple socioeconomic variables might, for example, reveal that most VGI in a certain region comes from upscale residential neighborhoods, and could further understanding of the social, political, and technological factors that affect how geographical data are developed, accessed, and interpreted (Elwood, 2007). Research is needed to define the limits of VGI in this context and to shed light on the social psychology of the producers of VGI.

Institutional review boards (IRBs) have emerged in recent years to protect the rights of human subjects in research projects, and yet there is wide variability in their capacity to apply and disseminate confidential research (Lane, 2003). Many IRBs are quite conservative vis-à-vis locational privacy, making it difficult for researchers to work with tracking data. This orientation could be a major impediment to useful research. Sieber (2004) has suggested some innovative ways in which IRBs could improve researchers' understanding of confidentiality issues, including how best to interpret, adapt, and apply nondisclosure techniques, but the challenge of developing ways to contront locational privacy issues remains (NRC, 2007b).

Turning to the evaluation of content and quality, VGI has been termed asserted information, to contrast it with the authority of traditional sources. While mapping agencies have developed elaborate mechanisms for quality control and assessment, the quality of VGI remains very much an open research issue (although in other areas of volunteered information, such as Wikipedia, some preliminary research results are now available, e.g., Read, 2006). Researchers working on this topic need to develop ways for educated citizens to produce not only volunteered geographical information but also volunteered geographical analysis. Given existing perspectives and methods, the geographical sciences could develop rubrics to assess and evaluate the quality of VGI (i.e., both the validity and accuracy of VGIs, as well as the quality of any metadata) and the accuracy of resulting maps. For example, Flanagin and Metzger (2008) discuss (1) emerging analyses and rubrics for geographical training and education of novices by experts; (2) assessment of the notoriety of systems (such as the level of trust users now have in Wikipedia, Google Earth, Citizendium, etc.); and (3) development of algorithms that reveal (via IP address) the source of content or compute the "reputation" of an author's entry as measured by its longevity. Researchers could investigate the thematic limits of VGI (i.e., the kinds of geographical information that is best acquired in this way, rather than by scholars or government authorities) and its ethics (what protections are needed for individual privacy, and the limits on what people should be able to report about others?).

In what ways does participation in VGI have the unintended effect of increasing the digital divide?

Discussions of neogeography and of what can be achieved today by citizen mappers rarely include the issue of the digital divide—the sharp contrast between those with effective access to digital technology and those with limited or no access. Although most people in high-income countries are used to the power of Google Earth, the vast majority of the world's citizens have no access to either the Internet or personal computers. Moreover the divide is growing, as certain groups acquire more and more technology and others continue with nothing. Since the proliferation of VGI could exacerbate the digital divide, it is important to understand better whether, and where, this might happen (e.g., in contrast to Figure 11.2, some parts of the world still don't yet "show up" because people there cannot contribute information).

In the free-for-all atmosphere of the Internet, it is easy to forget the impediments to accessing geographical data and tools. GIS software can be expensive and far beyond the resources of many. In other cases, governments actively seek to keep geographical technologies out of the reach of groups of people. We need to understand how spatial knowledge is shaped

by identity, power, and socioeconomic status, and how spatial data handling is socially and politically mediated (Harvey et al., 2005). Research in this vein will help us understand how we need to alter community planning paradigms and decision-making practices in order to more fully realize the potential of VGI, without exacerbating the digital divide.

Sui's (2008) call for a focus on equity and privacy in studies of VGI raises critical questions about the motivations and incentives for people to engage in VGI. For example, to what extent does the digital divide influence citizen participation? He asks whether the "wikification process" may enlarge disparities in society by allowing "the favored few to exploit the mediocre many," as opposed to narrowing the digital divide, thereby producing "digital dividends" for a broader community (Sui, 2008). Addressing these issues will require collaboration with the open-source software community, as it (1) already understands the relationships between security, privacy, functionality and freedom (Peterson, 2008), (2) is beginning to understand and implement the principle of developing software that is both citizen controlled, yet privacy oriented (Peterson, 2008), and (3) is often committed to closing the digital divide.

What and where are the most significant threats to human privacy as presented by emerging geographical technologies and how can we design technologies to provide protection?

Even as geographical technologies are enabling positive aspects of citizen mapping such as VGI, they also appear to be among those opening society up to a new kind of surveillance in the mapping *of* citizens (Pickles, 1991; Monmonier, 2002). As an example, Elwood (2008) cites www.RottenNeighbor.com, which allows people to post the location and perceived offenses of their neighbors. Richards (2008) reports that various shopping centers in the United Kingdom are now using the cell phone signals of customers to monitor which stores people visit and how long they stay there. Yang et al. (2008) propose an activity recognition system that would track people's movements throughout their home in order to help them perform forgotten tasks (such as taking medicine), choose which rooms to play music in, or diagnose a slow Internet connection. Such a system makes use of the existing Wi-Fi connections and Internet protocols already at play within a home network of PCs, printers, phones, TVs, and networked stereos. However, as highlighted by Claburn (2008), such systems also raise privacy issues. How will datasets be protected? Who will have access to them? And what will prevent them from being stolen or even subpoenaed? These questions point to the need for research into how new forms of knowledge production and access may affect privacy and facilitate new forms of surveillance (Elwood, 2008).

The core assumption of the LBS industry is that corporations will own and control locational information about their individual customers. This assumption leads to different technical challenges and research questions for situations involving both the public and private sectors (Raper et al., 2007). Researchers need to take up the challenge of developing the synthetic datasets that will limit "the risk of identification while providing broader access and maintaining most of the scientific value of the data" (NRC, 2007b: 2). We thus support the conclusions of the National Research Council that "various new technical procedures involving transforming data or creating synthetic datasets show promise for limiting the risk of identification while providing broader access and maintaining most of the scientific value of the data. However, these procedures have not been sufficiently studied to realistically determine their usefulness" (NRC, 2007b: 2).

Collaborations between academics and industry scientists can lead to the development of effective algorithms for "geographic encryption," also known as "geographic masking" (Kwan et al., 2004). There is a need for different ways of suppressing, resampling, or multiplying by random noise certain records in a geographical database (e.g., Armstrong et al., 1999), perturbing the underlying microdata rather than perturbing the database cells themselves (Lane, 2003), and developing other geomasking techniques for both continuous and categorical variables that can be applied locally (to a subset of records with a high disclosure risk) rather than globally (e.g., VanWey et al., 2005; Zimmerman et al., 2007). These approaches are supported by the NRC (2007b), which recommends that data stewards develop licensing agreements to provide increased access to linked social-spatial datasets that include confidential information. Bertino et al. (2008)

recommend further that development of standards for geographical data security and advanced geographical data protection is now critical. In addition, the work of Zandbergen (2008), which characterizes the capabilities of reverse geocoding (i.e., deriving an address from a position, rather than vice versa) using a range of different network analysis methods, offers a promising example of how research on this topic could make advances over the next 10 years.

The urgent need for work on privacy protections for locational data becomes clear when one considers that, despite efforts to ensure the privacy of personal information (e.g., protection of social security, credit card, and driver's license numbers), no explicit regulation currently protects locational privacy in the United States. It is important to note that data availability and concerns about privacy vary by culture. For example, in the United States, Google has responded to privacy concerns by testing and gradually implementing a face-blurring algorithm for its Street View service (Figure 11.3), but Canada has enacted an identity protection law, requiring Google to blur not only faces, but also license plates. Bitouk et al. (2008) have developed software that goes beyond the simple blurring of a face in a photograph to "swapping" the features in a face with random features from a library of faces (such as a Flickr library). The result is a composite photograph that changes the identity of the person in order to further protect his or her privacy.

Over the next 10 years, geographical scientists should continue research on responsible locational data release formats, while working to develop codes of practice for LBS use. The work of Onsrud (2003) and Solove and Rothenberg (2003) shows that there is great potential in collaborations with legal scholars to identify principles governing the dissemination of personal geographical information in various contexts. This will allow researchers to estimate the social benefits and costs of information dissemination, and to identify potential conflicts.

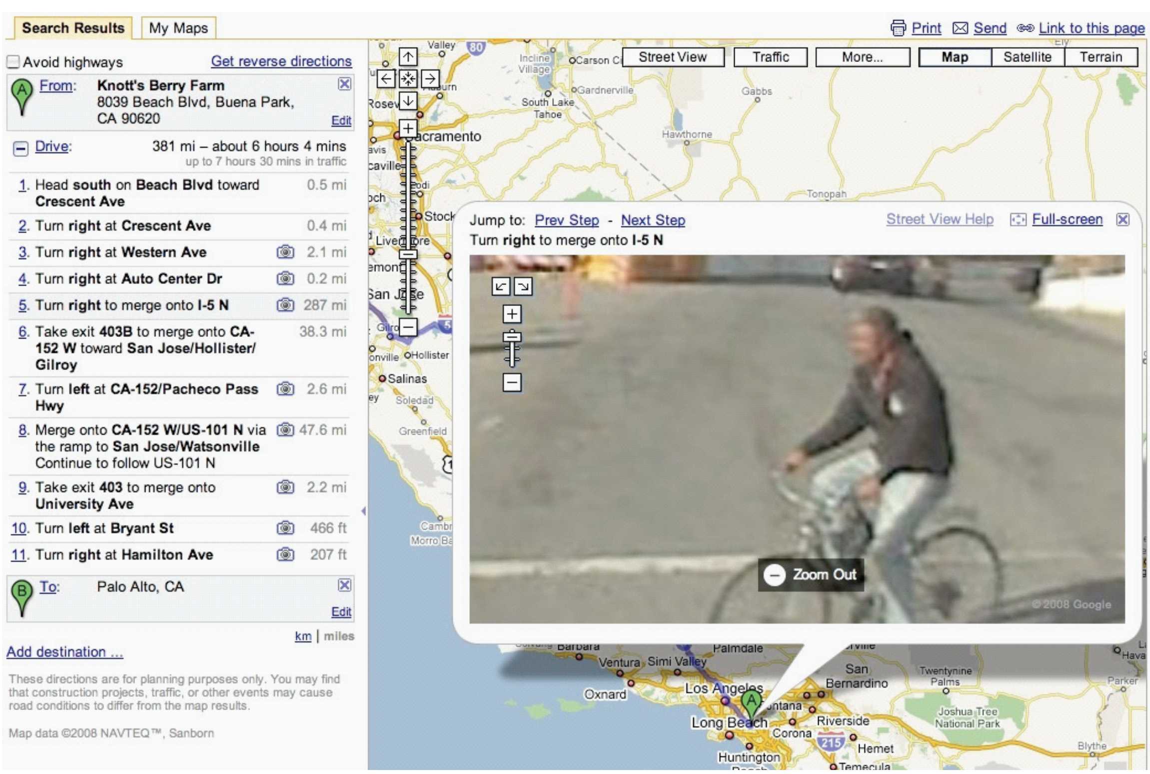


FIGURE 11.3 Implementation of the face-blurring algorithm in Google Street View. SOURCE: maps.google.com/help/maps/streetview (accessed January 20, 2010).

SUMMARY

The recent and stunning emergence of citizens as both the sources and subjects of mapping has serious implications for individual privacy and many related societal issues, as millions worldwide continue to create a global patchwork of geographical information. The geographical sciences are central to promoting understanding of the nature and responsible use of these new forms of data acquisition and dissemination.

Part III

Moving Forward

Moving Forward

The eleven questions in Part II speak to some of the fundamental challenges currently facing science and society. Given the extent and magnitude of the geographical transformations unfolding in the early 21st century, it is imperative to understand what is happening where, why changes are happening in particular places, and how the geographical sciences can best respond. The geographical sciences have had a growing impact across the sciences in recent years, and public awareness of the importance of geographical inquiry is growing. Nonetheless, moving forward requires a major effort to expand what the geographical sciences can do. This concluding section of the report outlines the key support systems that need to be enhanced as part of such an effort: research infrastructure, training, and outreach.

RESEARCH INFRASTRUCTURE

To date, most progress in the geographical sciences has been made through small, independent research initiatives that may be loosely coordinated, but often are not. Professional society meetings serve to bring researchers and research ideas together, but they do not have the resources to promote large-scale collaborations, nor is that their mandate. Yet as this report suggests, large-scale collaborations are important to address many geographical problems—collaborations that involve investments in technology and infrastructure and that draw on diverse perspectives and different types of data. The payoffs to such collaborations can be large, but so are the obstacles to making them happen. Those obstacles include gaps in available data on which large-scale collaborations can be based, and insufficient tools and mechanisms for bridging different monitoring and analysis initiatives. It follows that enhancements in research infrastructure should focus on data development, storage, and sharing, and the development of formal institutions and arrangements designed to facilitate meaningful collaborations.

The Human Genome Project provides a model for what can be achieved through large-scale, technologically supported collaboration. A first step to making similar strides in the geographical sciences would be to hold workshops and conferences focused on specific strategic directions, with the goal of identifying ways of moving them forward. These workshops could help clarify the costs, value, stakeholders, and viability of collaborations and suggest concrete steps that could be taken to build forward-looking research programs.

In terms of infrastructure, much of today's science focuses on complex issues such as global climate change, species extinction, economic modeling, or urban crime—problems that often involve the analysis of massive amounts of data using tools that are capable of exploring the behavior of complex systems through rapid and increasingly realistic simulations. Many of the tools used by the geographical sciences are of this nature; yet, in some important respects, they are not adequate to the task. To move the geographical science enterprise forward, at least two distinct infrastructure requirements need to be addressed: (1) sensors and data storage and retrieval and (2) cyberinfrastructure and tools.

Sensors and Data Storage and Retrieval

A key component of geographical analysis is the focus on spatial variations, or the tracking of phenomena as they vary across the surface of Earth. Many geographical scientists rely on remote sensing from satellites, a technology with high initial costs (billions of dollars have been invested in the "big iron" of NASA's Earth Observing System program over the past two decades), but one that has yielded astonishingly productive results in the form of massive amounts of fine-resolution data that can be used to map and analyze ocean temperatures, land cover, urban growth, and a host of other phenomena. Sizeable investments have also been made in the technologies that allow for the processing, storage, and dissemination of information, allowing thousands of scientists worldwide to benefit from the power of space-based sensors. It is important for these investments to continue, with commitments to develop new sensors as the science of sensing progresses; to replace aging satellites as they fail, thus ensuring reliable longitudinal series; and to explore the capabilities of each new sensor once it is in orbit. The geographical sciences can contribute to, and benefit from, all of these areas; indeed they have a vested interest in doing so, given the importance of this source of data to many of the questions posed in Part II.

Recently, the scientific community has begun to understand the potential of ground-based remote sensing. Ground-based sensor networks are often envisioned as arrays of fixed, inert sensors distributed across the landscape, each one capable of measuring useful properties of its immediate environment, determining its own location, and transmitting these measurements and locations to a central service where data can be integrated and disseminated to the scientific community. Large projects to install networks of value to the geographical sciences have been proposed by ecologists (National Ecological Observatory Network), oceanographers (National Science Foundation's [NSF's] Ocean Observatories Initiative), hydrologists (the WATERS network), and others.

As discussed in Chapter 10, however, there are limits to what can be sensed remotely, whether from space or from land, creating an imbalance in the data supply for studies such as those in the geographical sciences that deal with social and environmental systems. Traffic sensors on highways can provide useful information, but more generally there is little prospect of providing the kinds of data required to support the geographical perspective on social systems or on the social dimensions of coupled natural–human systems. The U.S. Census, which used to provide highly detailed decennial snapshots of the spatial differentiation of the population, will in the future provide only the most basic demographic data; the more detailed socioeconomic questions will now be covered by the American Community Survey, a rolling monthly sample that will provide finer temporal resolution but much coarser spatial resolution.

There is a growing imbalance between environmental and social data infrastructures. It is important to understand environmental systems, of course, but solving many of society's pressing problems requires an equivalent level of understanding of social systems and of interactions between the environmental and the social. Indeed, human activity is both the cause of much environmental change and the recipient of many of its impacts. A possible source of social data has already been discussed in Chapter 11: the potential of humans to act as sensors of important social variables through a form of citizen science. Although this approach has already proved valuable in many areas, systematic research is needed into quality assurance, techniques for integration and dissemination, and organizational structures if it is ever to achieve its apparent promise. Other options, such as facilitating access to the administrative and commercial records that are largely off-limits to scientists, hold promise only if the obvious difficulties of ownership and confidentiality can be addressed.

One approach to resolving issues of access might be to create tightly controlled environments in which scientists could work with sensitive data but leave only with results that protected the confidentiality of the original records. This approach has been tried with some success by the U.S. Census Bureau, which has established firewalled data centers at selected universities where researchers can make custom requests of individual census records. An NRC report (NRC, 2007b) argues that this approach could be implemented through appropriately designed software, allowing researchers to access a range of confidential databases remotely through the Internet, thus avoiding the

necessity for physical presence at a center. Implementing such a system could help researchers in the geographical sciences gain access to, and use, the social data they need to address key questions about the changing human geography of the planet.

Cyberinfrastructure and Tools

An NSF report (2003) argued that in the future, science will require a new kind of infrastructure—a cyberinfrastructure—to respond effectively to emerging challenges. Cyberinfrastructure encompasses the computers, networks, and storage devices of scientific computing; the sensors, software, tools, and communications of a networked scientific world; and the virtual communities that have to collaborate to make substantial progress. All of the foregoing require massive investment. Substantial investments have already been made by the NSF in building cyberinfrastructure through awards for the acquisition of high-performance computing systems and for the building of virtual communities of networked scholars. The 2003 NSF report has also been followed by others offering more specialized perspectives on the role of cyberinfrastructure in the social sciences (Berman and Brady, 2005), the humanities (American Council of Learned Societies, 2006), and several individual disciplines.[1] Yet to date little of the cyberinfrastructure discussion or investment has focused on the geographical sciences.

Because the geographical world is infinitely complex, any attempt to represent it, whether in the form of a paper map or a digital database, requires making difficult decisions about what to include and what to leave out. One strategy is to ignore spatial detail, rejecting information about variation that occurs over distances smaller than some declared spatial resolution. A related approach is to lump together approximately homogeneous areas or regions and ignore all variation within them. Other types of variation can be adequately captured by taking samples at appropriately spaced measurement points. Numerous commercial firms have adopted their own proprietary formats in the past (e.g., ESRI), and several national and international organizations have promulgated standards (e.g., Open Geospatial Consortium and the Federal Geographic Data Committee). As a result, many hundreds of geographical data formats now exist, creating headaches for anyone wanting to share data or integrate data from multiple sources (Goodchild et al., 1999).

Nonetheless much progress has been made in achieving a greater degree of interoperability. The Open Geospatial Consortium was formed in the 1990s to address interoperability issues, and most high-income countries are now actively engaged in developing their spatial data infrastructures, following the guidance provided by a report under the aegis of the NRC's Mapping Science Committee (NRC, 1993). In this regard, the geographical sciences are at a distinct advantage relative to many sciences, because not only researchers but also government agencies, corporations, and nongovernmental organizations are willing to support and invest in steps to improve the sharing of geographical data. The creation of mashups by combining geographically referenced information from different Web sites is one demonstration of the power of this new level of interoperability (Chapter 10).

In other respects, however, the research community is unable to benefit by hitching its wagon to broader efforts. Although great progress has been made in the sharing of data, there has been little comparable progress in the infrastructure needed to share the tools of analysis or the software of simulation modeling. The computer codes being created to model complex geographical systems are largely developed in low-level languages and are unlikely to be reusable by others. There are no digital libraries of tools and software, and no standards for their documentation and description. There are no GIS software environments designed specifically for the needs of K-12 education (NRC, 2006), and the products on which most of our students are trained were too often developed to support inventory and management rather than scientific research. By and large, these tools have not received the kinds of funding needed to ensure that they are rigorously engineered, robust, well documented, and widely disseminated.

By its very nature, geographical information is distinct from the kinds of information acquired and analyzed in those disciplines that proceed by controlled experiment. The foundations of statistical analysis were developed in disciplines such as psychology, where it was reasonable to believe that the members of a sample of subjects had been randomly and independently

[1] For a complete listing, see www.nsf.gov/crssprgm/ci-team/ (accessed December 15, 2009).

chosen from some larger population and that results obtained from the sample could then be generalized, with appropriate caveats, to statements about the population. The geographical sciences are dominated by so-called natural experiments, where researchers have little if any control over the sampling process. Thus it is unreasonable to make the assumptions of a controlled experiment when dealing, for example, with a study of Los Angeles using data about its census tracts. Conditions in adjacent tracts are not independent, and there is no larger population from which the tracts have been randomly drawn and about which more general statements can be made.

Instead, the analysis of geographical data requires a set of highly distinct and specialized techniques known collectively as spatial data analysis. The assumptions, data structures, and techniques of spatial data analysis are very different from those of standard statistical analysis and require specially designed software packages commonly known as GIS. Their effective use may even require the unlearning of much standard statistics and replacing them with an alternative paradigm that places more emphasis on visualization and on analyses that are not easily generalizable because they are shaped by place-based differences.

All of this argues, then, for a specialized infrastructure for the geographical sciences with its own distinct mechanisms for acquiring, documenting, sharing, analyzing, and modeling. Much of that infrastructure has already been built, thanks primarily to the importance of geographical information in many areas of human activity well outside the scientific realm. Other parts of the infrastructure, however, have not yet received the kinds of investments or attention that geographical inquiry requires. The supply of data is important, but the supply of tools, in the form of software, is at least as important.

Recently, efforts have been made to envision the next generation of spatial analytical tools by thinking not only of the future of GIS, which is often presented as the key technology for spatial analysis, but also of the future of virtual globes (Chapter 10). Because the commercial sector is unlikely to see profit in investments of this nature, given their orientation to a comparatively small market of researchers, research funding agencies, particularly the NSF, will have to stimulate advances in this particular area of infrastructure.

Addressing Infrastructure Challenges

When combined, the arguments made in the previous two subsections point to the need for a comprehensive approach to the growing gap in data for the geographical sciences and to the need to develop and disseminate a new generation of more powerful tools. One way to confront this need is to develop a virtual center, implemented as a set of Internet services, that would give researchers limited access to unconventional and frequently sensitive data sources, together with the tools needed for analysis. Such a center would establish the necessary protocols and implement them in software. It could also negotiate with individuals, commercial providers, government agencies, and the custodians of sensor networks to provide the necessary assurances that confidentiality and other concerns would not be compromised. It could develop the techniques needed to integrate diverse data sources, with themes spanning the social-environmental divide, and it could offer them in a reliable, robust, and easy-to-use fashion to researchers from a range of disciplines. It would have procedures for long-term data preservation, the lack of which is a growing across-the-board problem in science. The interface presented to the researcher would be easy to use but would embody the best scientific principles in documentation and metadata structure. In essence, this center could resolve a growing problem by providing a brokering service between the researcher and the potential supplier of useful data.

A suitable next step, then, would be to launch a series of workshops focused on identifying the kinds of infrastructure investments needed to support research in the geographical sciences, as well as research more broadly that makes use of a geographical perspective. This committee believes that this specific kind of infrastructure investment could play a significant role in addressing the types of strategic directions for the geographical sciences identified in Part II of this report.

TRAINING

It is ironic that, at a time when the importance of the approaches and tools of the geographical sciences is increasingly recognized, the need to improve training in the geographical sciences remains critical. Without curricular changes aimed at promoting geographical

understanding, spatial thinking, and geographical research skills, however, the graduates of our educational institutions will not possess the insights and tools needed to address the complex problems identified in this report. Therefore a new, dedicated, and proactive approach to formal geographical education is essential to support the strategic directions for the geographical sciences identified and discussed in this report.

After a period of neglect, geographical concepts and ideas have been carving out more of a role in the curriculum in recent years (Bednarz et al., 2006; Murphy, 2007).[2] Yet pedagogic programs with a significant geographical component are weak or nonexistent at the many schools, colleges, and universities. Moreover, even where significant training opportunities exist, consideration needs to be given as to whether programs are providing students with the background and skills needed to tackle the types of strategic questions enunciated in this report. Such programs need to provide students with the tools to address large-scale, multidisciplinary problems and ensure that instruction in skills and techniques is accompanied by training in the nature of a geographical perspective and the characteristics of geographical analysis. Strengthening and deepening geographical education is vital both to building a substantial coterie of geographical scientists who can pursue the kind of work outlined in this report and to promoting the informed, ethical, and sensitive use of geographical technologies in the broader community.

Addressing the training challenge requires finding ways to broaden and deepen student understanding of key geographical patterns and processes, enhancing critical spatial thinking skills, and deepening student grasp of the structure and functions of geographical technologies, including their awareness of the appropriate contexts in which those technologies should and should not be used. The *Learning to Think Spatially* report (NRC, 2006) provides a starting point on the spatial-learning front, but much work remains to be done. What is needed is the implementation and expansion of programs focused on teacher training and support in geographical concepts and techniques, the development of new curricular materials, the seizing of opportunities to create courses and programs of study with a significant geographical component, and the infusion of the ideas and approaches of the geographical sciences across the curriculum.

The latter issue is of particular importance in institutions that lack formal geography or geographical science programs. Efforts need to be made to strengthen the geographical component of existing science, earth science, and social science courses. Promising new curriculum projects demonstrate the potential of this approach. These include projects sponsored by professional organizations such as the Association of American Geographers (AAG) and the National Council for Geographic Education. Project GeoSTART is a NASA-funded project linking spatial thinking skills, geographical technologies, and geoscience topics (specifically as they relate to hurricanes). The *Teacher's Guide to Modern Geography* is a project funded by the U.S. Department of Education that links spatial thinking skills across the curriculum in subjects such as mathematics, history, and science. And the University Consortium for Geographic Information Science has developed a model curriculum focused on the technological aspects of the geographical sciences (DiBiase et al., 2006).

There are growing opportunities for bringing geographical science perspectives into funded educational and research programs. The Center for Spatially Integrated Social Science (CSISS) is an NSF-funded program that "recognizes the growing significance of space, spatiality, location, and place in social science research [and] seeks to develop unrestricted access to tools and perspectives that will advance the spatial analytic capabilities of researchers throughout the social sciences."[3] By providing online tutorials, text and online reference materials, and workshops, CSISS offers a model for the diffusion of the geographical science approach to all disciplines, not just the social sciences. In addition, the Spatial Intelligence and Learning Center, funded through the NSF's Sciences of Learning Centers program, "brings together scientists and educators ... to pursue the overarching goals of: (a) understanding spatial learning and (b) using this knowledge to develop

[2]At the K-12 levels, several initiatives help explain the growing profile of geographical perspectives in education, including the National Geographic Society's "Geographic Alliance" program (Dulli, 1994), the development of widely acclaimed state standards for geography education (Boehm and Bednarz, 1994), and the highly successful addition of Human Geography to the College Board's Advanced Placement program (Murphy, 2007).

[3]See www.csiss.org/ (accessed December 15, 2009).

BOX 1
Key Questions for Training Programs in Geography/Geographical Sciences

- Are lower-division courses introducing undergraduates to the problems that are the focus of the questions raised in Part II in ways that will foster understanding and a desire to pursue additional study and research?
- Are there opportunities for undergraduate research that can build research skills and foster interest in advanced work?
- Are the techniques courses being offered sufficiently grounded in concepts and theory so that students see the geographical sciences as a way of thinking, not just a set of computer programs?
- Are graduate programs providing both enough generalist training to allow students to ask big questions that cut across traditional domains and enough specialist training to give them the insights and tools needed to address those questions?
- Are students being encouraged to think across long-standing divides between the human and the physical, the social and the technological?
- Are students learning not only to look for patterns, regions, and spaces of meaning, but also to think critically about them?
- Are students being encouraged to pursue academic or research careers, and are programs configured in ways that support those pursuits?
- Are programs open to students and scholars in the many disciplines that are developing interests in the geographical sciences?

programs and technologies that will transform educational practice, helping learners to develop the skills required to compete in a global economy."[4] The emphasis on the development of human capital is clear, as is the explicit focus on the transfer of research to education in a domain central to the geographical sciences.

Institutions offering advanced degrees in geography or geographical science are on the front line of producing the next generation of specialists. They face a set of programmatic questions that arise directly from the strategic questions in Part II (see Box 1). Addressing these questions can help build student interest in the geographical sciences, give advanced students the conceptual and technical skills needed to address many of the strategic questions raised in this report, and promote an expanding community of researchers and scholars who can push the research frontiers highlighted in Part II.

Enhancing training opportunities for graduate students and early career faculty will likely advance the next generation of specialists. The NSF Integrative Graduate Education and Research Traineeship (IGERT) program provides opportunities to build competence across the breadth of the geographical sciences by linking them with other disciplines. There are, for example, affinities between the geographical sciences and epidemiology, engineering, archaeology, sociology, psychology, and the geosciences. Exploiting those affinities would meet the IGERT intent "to catalyze a cultural change in graduate education, for students, faculty, and institutions, by establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries."[5] Other avenues that might be pursued include interdisciplinary summer workshops focused on the applicability of geographical approaches to research on particular topics and the development of research centers focused on particular strategic questions.

The challenge of developing and training a sizeable cadre of specialists who can advance work on the types of questions outlined in Part II is substantial. Ways need to be found to expose more students to geographical ideas and tools and to enhance the research skills of those with particular aptitude and interest in the geographical sciences. Addressing this challenge will require building on the promising recent initiatives outlined above and looking for new ways of infusing the concepts, techniques, and research approaches of the geographical sciences across the curriculum.

OUTREACH

Policy makers, administrators, media figures, and other influential individuals are in a position to use, or ignore, what the geographical sciences have to offer, but they can only make informed choices if they are aware of

[4]See www.spatiallearning.org/ (accessed December 15, 2009).

[5]See www.nsf.gov/funding/pgm_summ.jsp?pims_id=12759 (accessed December 15, 2009).

what the geographical sciences can contribute. Many are not in this position because only recently have the geographical sciences begun to play a more significant role in public debate (Murphy, 2006). It follows that efforts are needed to promote outreach and informal education about the nature and potential contributions of the geographical sciences.

Improving external communication is a challenge faced across the sciences, but the relevance of geographical understanding to many policy choices and to everyday life renders external communication a particular imperative (Moseley, 2010). Consider, for example, the growing pervasiveness of geographical technologies. Countless people are using the Global Positioning System, virtual maps, and location-based services in their daily lives, and decision makers are constantly being presented with maps and information derived from them. Yet whether these technologies are being used in productive and informed ways is a matter of considerable concern, given the lack of general understanding of how they work and how the choices that are made about data, spatial range, and scale influence the visualizations they produce and the options they suggest (Harvey et al., 2005). Only by expanding familiarity with such matters can we hope to bridge the knowledge gap that currently exists between those who develop these technologies and those who use them.

Identifying opportunities for informal education is essential to promote outreach, develop the skills to translate complex ideas into language and evocative visualizations that can be broadly grasped (Figure 1), and build bridges between the geographical science community and those involved in developing and influencing policy. The informal education challenge is significant, but critical, given that education is no longer seen as the exclusive responsibility of a formal system based on physical presence in schools. Many of the perspectives and tools of the geographical sciences lend themselves to online distance education, virtual networking through affinity groups, and participation in activities, such as orienteering, that have a locational component. There are already rapidly growing efforts to develop online educational resources with a geographical component, such as the AAG's Center for Global

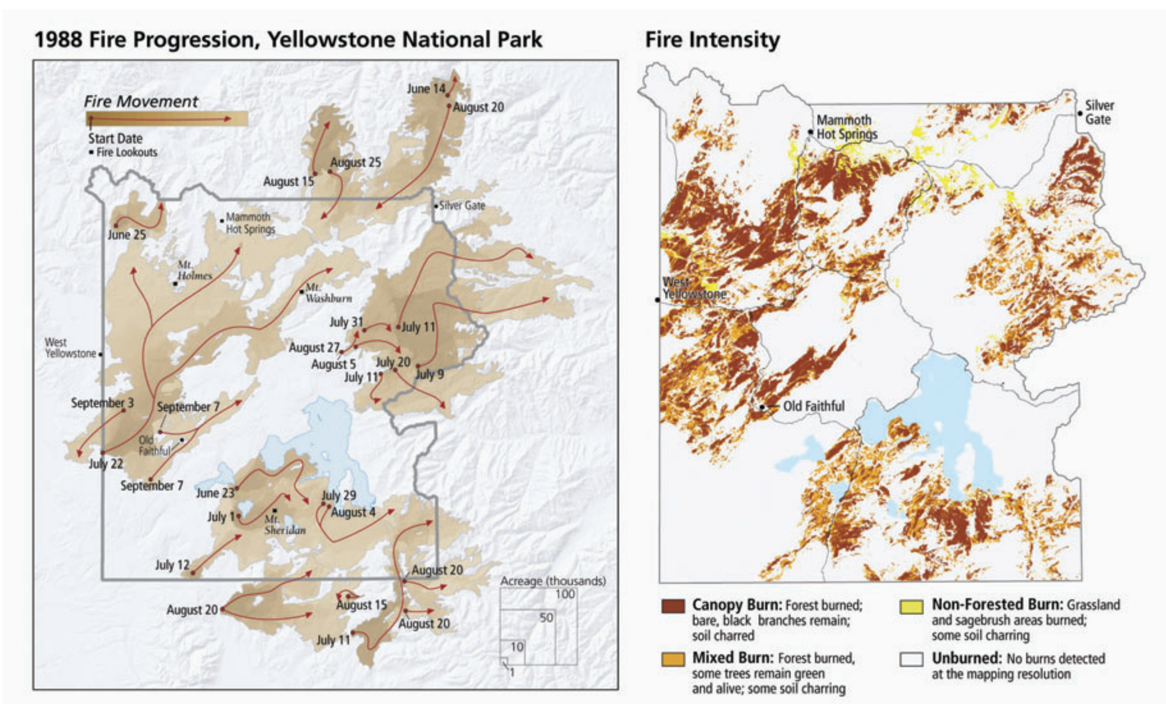


FIGURE 1 Maps showing the spatial and temporal characteristics of the massive fires that swept through Yellowstone National Forest in summer 1988. Geographical visualizations of this sort enhance public understanding of what happened and help policy makers plan for the future. SOURCE: Copyright 2009, University of Oregon, Atlas of Yellowstone (in production); Rick Wallen, Yellowstone National Park.

BOX 2
Policy and Media Fellowships in Other Research Communities

If programs similar to the ones listed below were designed and implemented for the geographical sciences, students could work with policy and media organizations to apply the latest research and analytical tools to everything from political to environmental to health-related reporting.

John A. Knauss Marine Policy Fellowship: Cosponsored by the National Oceanic and Atmospheric Administration (NOAA) and the National Sea Grant College Program, this federal program, provides an opportunity for students with an interest in oceanic, coastal, and Great Lakes issues to gain valuable experience by working in either the legislative or executive branch of the federal government. Past fellows have held positions in the Senate and House of Representatives, as well as in NOAA, the Department of State, and the Department of the Interior.

Jefferson Science Fellows: Recognizing the importance of science, technology, and engineering (STE) in advancing government policy, specifically U.S. foreign policy, this program is administered by the National Academies and supported by numerous organizations, including scientific societies and the U.S. Department of State. The program is seen as providing "a new model for engaging American academic STE communities in the formulation and implementation of U.S. foreign policy."

Mass Media Science and Engineering Fellows Program: Sponsored by the American Association for the Advancement of Science, this program places graduate and postgraduate students in various roles in media organizations.

Aldo Leopold Leadership Program: The program's goal is to advance environmental decision making through the development of academic scientists as effective leaders and communicators. The program provides intensive interactive training sessions where fellows are taught methods to engage with and communicate to a variety of nonscientific audiences.

AAAS Science and Technology Policy Fellowship Program: This program promotes links between federal decision makers and scientific professionals concerned with social and environmental issues. The fellowships educate scientists about the federal policy-making process and put policy makers in contact with scientists who can advise them about scientific and technical issues bearing on policy decisions.

Geography Education,[6] which provides open Internet access to course modules focused on social, economic, and environmental issues. Other initiatives of this sort, including ones targeted at the types of strategic questions raised in this report, could help widen the reach of the geographical sciences.

The task of facilitating the translation of complex ideas into language and visualizations that can be broadly grasped is inextricably tied to the challenge of building bridges with the media and policy makers (de Blij, 2005). A coherent set of activities designed to promote communication skills and facilitate external connections could range from workshops, conferences, and professional opportunities bringing geographical scientists and journalists together to learn how to communicate important scientific findings more effectively to opportunities for geographical scientists to serve as staff members in congressional offices or within the executive branch; to fellowships that would allow geographical scientists to become more effective communicators and informal educators (see Box 2).

A strategy of coherent public outreach can build on the success of existing models designed to improve linkages across the geographical science community, the public policy and private sectors, nongovernmental organizations, and the media and general public. The AAG, for example, has held two successful "Mapping the News" conferences that brought together geographers and journalists to share ideas and information. That organization has also appointed a media officer and regularly hosts media sessions at its annual meetings that educate geographers about how to communicate their research findings to the public. The American Geographical Society has launched an increasingly successful program aimed at promoting the writing and placement of opinion pieces (op-eds) by geographers and also maintains a Media Center that provides media representatives with geographers to speak on issues of

[6]See www.aag.org/Education/center/cgge-aag%20site/index.html (accessed December 15, 2009).

geographical relevance. These types of outreach efforts could be incorporated into geography and geographical science graduate programs to make communication with the public and policy makers more central to graduate education rather than a skill acquired later in a research career, if at all.

The entire geographical sciences community—federal program leaders, academic institutions, professional societies, nonprofits—has an important role to play in maximizing the community's reach and impact. If organized, the community could actively identify opportunities for the dissemination of geographical ideas, information, and research results to specific audiences, including the policy sector. The community could also create a mechanism through which geographical scientists could be put into contact with various foundations and think tanks—enhancing the prospects that partnerships would emerge that would promote understanding of such topics as disease hotspots, human vulnerability to famine or natural disasters, or trends in inequality at the subnational scale. The community could also pursue efforts to make better connections with the media and other key audiences by hosting annual seminars and policy forums.

CONCLUSION

The coming decade will almost certainly be one in which concerns about resource use and availability, environmental change, socioeconomic divisions, human security, and technological change will figure prominently on scientific and social agendas. The geographical sciences have a critical role to play in elucidating those concerns. A well-developed and well-connected geographical science enterprise is in a position to provide insights of scientific and policy relevance on a range of demographic and consumption issues, the changing character of Earth's land surface and environmental systems, globalization, the nature and significance of shifting social and political arrangements, and the potential and limitations of geographical technologies. The geographical sciences cannot tackle these matters alone, but without their perspectives and tools, our collective understanding of the changes that are remaking the world will be impoverished.

The time is ripe, then, to forge an increasingly sophisticated, well-organized, and powerful geographical science that is embedded in a progressively more geographically enabled world. A geographically enabled world is one in which a substantial body of scientists has the training and infrastructure needed to advance the frontiers of geographical science. It is one in which the larger community of scientists is aware of, and can build on, the contributions of the geographical sciences. It is one in which policy is informed by the approaches and representations of the geographical sciences, and in which members of the general public have a sufficient grasp of geographical ideas, concepts, and techniques to be able to make intelligent use of the geographical representations and tools that are increasingly a part of modern life. Realizing the vision of a geographically enabled world offers the prospect of new and important insights into the health of the planet and the well-being of the people who occupy it.

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Appendixes

Appendix A

Committee and Staff Biographies

Alexander B. Murphy (*Chair*) is professor of geography and former head of the Department of Geography at the University of Oregon, where he also holds the James F. and Shirley K. Rippey Chair in Liberal Arts and Sciences. He specializes in cultural and political geography, with a regional emphasis on Europe. Professor Murphy is a past president of the Association of American Geographers (2003-2004) and current senior vice president of the American Geographical Society. He was a co-editor of *Progress in Human Geography* for 11 years, and he currently co-edits *Eurasian Geography and Economics*. In the late 1990s he chaired the national committee that oversaw the addition of geography to the College Board's Advanced Placement program. Professor Murphy is the author of more than 80 articles and several books, including *The Regional Dynamics of Language Differentiation in Belgium* (University of Chicago, 1988), *Cultural Encounters with the Environment* (edited with Douglas Johnson; Rowman & Littlefield, 2000), *Human Geography: Culture, Society, and Space*, 9th ed. (with Erin Fouberg and Harm de Blij; Wiley, 2009), and *The European Cultural Area: A Systematic Geography*, 5th ed. (with Terry Jordan-Bychkov and Bella Bychkova Jordan). Professor Murphy is the recipient of numerous grants and awards, including a Fulbright-Hays Research Grant in 1985, a National Endowment for the Humanities Fellowship in 1991, a National Science Foundation Presidential Young Investigator Award in the mid-1990s, a National Council for Geographic Education Distinguished Teaching Award in 2001, and the Association of American Geographers' Gilbert Grosvenor Honors Award for Geographic Education. Professor Murphy holds a B.A. in archaeology from Yale University, a law degree from the Columbia University School of Law, and a Ph.D. in geography from the University of Chicago.

Nancy Colleton is the president of the Institute for Global Environmental Strategies (IGES), a nonprofit organization located in Arlington, Virginia. She specializes in advancing environmental information capabilities and services—primarily Earth observations—and works to communicate their critical role in responding to global challenges such as climate change. Ms. Colleton also leads the Alliance for Earth Observations—an informal confederation of industry, academic, and nongovernmental organizations that works to ensure the rapid and broad delivery of the timely, comprehensive, and accurate environmental information for improved decision making. She cochairs the Environmental Information Services Working Group of the National Oceanic and Atmospheric Administration Science Advisory Board; is a board member of the GeoEye Foundation; and leads the newly established Specialty Group on Environmental Information for the International Union for Conservation of Nature. Ms. Colleton holds a B.A. degree from Hood College.

Roger M. Downs is professor of geography and former head of the Department of Geography at the Pennsylvania State University. He has chaired the NRC Geographical Sciences Committee and held a permanent position at the Johns Hopkins University, and sabbatical positions at Colgate University, the Uni-

versity of Washington, and the National Geographical Society. He holds B.A. (first class) and Ph.D. degrees from the University of Bristol, and has received honors from the National Geographic Society, the Association of American Geographers, and the National Council for Geographic Education. He has served as writing coordinator for the Geography Education Standards Project, and chaired the NRC study on Learning to Think Spatially: GIS as a Support System in the K-12 Curriculum. He has published three books and nearly 100 articles, reports, and reviews.

Michael F. Goodchild (NAS) is professor of geography and director of the Center for Spatial Studies and Center for Spatially Integrated Social Science at the University of California, Santa Barbara. He is also chair of the Executive Committee of the National Center for Geographic Information and Analysis and associate director of the Alexandria Digital Library. He taught at the University of Western Ontario for 19 years before moving to his present position in 1988. His research interests focus on the generic issues of geographic information, including accuracy and the modeling of uncertainty, the design of spatial decision-support systems, the development of methods of spatial analysis, and data structures for global geographic information systems. He has received several awards and published numerous books and journal articles. He is a member of the National Academy of Sciences, served on the Geographical Sciences Committee, and was a member and a chair of the National Research Council's Mapping Science Committee. He received a B.A. in physics from Cambridge University and a Ph.D. in geography from McMaster University.

Susan Hanson (NAS) is research professor of geography at Clark University. She is an urban geographer with interests in gender and economy, transportation, local labor markets, and sustainability. Dr. Hanson has been an editor of three geography journals—*Economic Geography*, the *Annals of the Association of American Geographers*, and *The Professional Geographer*—and currently serves on the editorial boards of several other journals including *Annals of the Association of American Geographers*, *Proceedings of the National Academy of Sciences*, and *Journal of Geography in Higher Education.* Dr. Hanson is a member of the National Academy of Sciences, past member of the Geographical Sciences Committee, past president of the Association of American Geographers (AAG), and has served as director of Clark's School of Geography (1988-1995; 2002-2004). She was the recipient of AAG's Lifetime Achievement Award in 2003. Dr. Hanson received her B.A. in geography from Middlebury College and her Ph.D. in geography from Northwestern University.

Victoria A. Lawson is professor of geography at the University of Washington and was chair of the Geography Department from 1997 to 2000. She has held several leadership positions at the Association of American Geographers, serving as president and national councilor. Dr. Lawson holds a Ph.D. and M.A. in geography from Ohio State University and a B.A. in social sciences from the University of Leicester. Her theoretical and empirical work is broadly concerned with the social and economic effects of global economic restructuring across North and South America. In addition, she is interested in three scholarly literatures: first, feminist care ethics; second, development studies work on neo-liberal modernization and globalization, the transformation of work, and poverty/inequality processes; and third, migration theory. She received several awards including the University of Washington Distinguished Teaching Award (1996). She is the North American editor for *Progress in Human Geography*, and has served on the editorial boards of *Annals of the Association of American Geographers* (1998-2006), *The Professional Geographer* (1992-1996), and *Economic Geography* (2002-present). She is a member of the National Academies Standing Committee on the Geographical Sciences, and she was a scholar on the Advisory Committee to the National Geography Education Standards Project of the National Council for Geographic Education (1993).

Glen MacDonald is presidential chair and director of the Institute of the Environment and a professor of geography, ecology, and evolutionary biology at the University of California, Los Angeles (UCLA). Previously, he served as a faculty member at McMaster University and a visiting fellow at Clare Hall, Cambridge University and Saint Catherine's College, Oxford. He was a Guggenheim Fellow from 2008 to 2009. The focus of Dr. MacDonald's research is long-term climatic and environmental change and the impact of such changes

on plants, animals, and humans. He uses a variety of archives to reconstruct past climate and environments including fossil pollen, plant macrofossils, tree rings, fossil insects, elemental geochemistry, stable isotopes, population genetics, and historical documents, artwork, and maps. Dr. MacDonald has published more than 120 peer-reviewed journal articles and numerous book chapters, reports, and other pieces, as well as an award-winning text on biogeography (*Biogeography: Time, Space and Life,* Wiley). He was elected a fellow of the American Association for the Advancement of Science and has won the McMaster University Award for Teaching Excellence and the UCLA Distinguished Teaching Award. Dr. MacDonald has served as the cochair of the National Science Foundation PARCS (Paleoenvironmental Arctic Sciences) program, chair of the Association of American Geographers Biogeography Specialty Group, and international coordinator (global change) for the International Boreal Forest Research Association, as well as associate editor or editorial board member for the *Annals of the American Association of Geographers, Geography Compass, Journal of Biogeography,* and *Physical Geography.* He received an A.B. degree in geography with highest honors and distinction from the University of California, Berkeley, an M.Sc. in geography from the University of Calgary, and a Ph.D. in botany from the University of Toronto.

Francis J. Magilligan is a professor in the Geography Department of Dartmouth College. His research interests focus primarily on fluvial geomorphology and surface water hydrology. In particular, his research addresses stream channel and watershed response to environmental change. He is a member of the Association of American Geographers (AAG), the Geological Society of America, and the American Geophysical Union. Dr. Magilligan has published more than 30 papers, and he has served as chair of the AAG Geomorphology Specialty Group and on the AAG Editorial Board. He received a B.A. in geography from Boston University, an M.S. in water resources management, an M.S. in geography, and a Ph.D. in geography from the University of Wisconsin at Madison.

William G. Moseley is associate professor of geography and director of the African Studies Program at Macalester College. He is a development and human-environment geographer with particular expertise in political ecology, tropical agriculture, environmental and development policy, livelihood security, and West Africa and southern Africa. Before becoming an academic, he worked for 10 years in the field of international development. His scholarly publications include 4 books, as well as more than 50 peer-reviewed journal articles and book chapters. He is also a committed public scholar who has published op-eds in such outlets as the *International Herald Tribune*, the *Christian Science Monitor*, the *San Francisco Chronicle*, and the *Chronicle of Higher Education*. He is chair of the national councilors of the Association of American Geographers (AAG), chair of the cultural and political ecology specialty group of the AAG, and editor of the *African Geographical Review*. His research has been funded by the National Science Foundation, the Fulbright-Hays Faculty Research Abroad Program, and the American Geographical Society McColl Family Fellowship.

Colin Polsky is an associate professor at the Clark University Graduate School of Geography. He is also director of the Human-Environment Regional Observatory (HERO) program, which provides opportunities for undergraduate and graduate students to analyze the causes and consequences of global environmental changes at local scales in faculty-led research projects, and research assistant professor at the George Perkins Marsh Institute. Dr. Polsky is a geographer specializing in the human dimensions of global environmental change, emphasizing the statistical analysis of vulnerability to climate change. He has explored ways to blend quantitative and qualitative methods for the study of social and ecological vulnerability to environmental changes in the Arctic (with a focus on traditional reindeer herding), the U.S. Great Plains (with a focus on contemporary agriculture), and central and eastern Massachusetts (with a focus on suburban water management). Dr. Polsky received his Ph.D. and M.S. (geography) degrees from the Pennsylvania State University, where he was a National Science Foundation Graduate Research Fellow, and B.S. (mathematics) and B.A. (humanities, French) degrees from the University of Texas at Austin. He has also completed a 2-year postdoctoral fellowship at Harvard University, with the Research and Assessment Systems for Sustainability program at the Belfer

Center for Science and International Affairs, John F. Kennedy School of Government.

Karen C. Seto is an associate professor in the School of Forestry and Environmental Studies at Yale University. She was on faculty at Stanford University for 8 years prior to joining Yale in 2008. The focus of Dr. Seto's research is the human transformation of Earth's surface, with an emphasis on urbanization, and the consequences of land conversion for the environment. She has ongoing projects in China, India, and Vietnam, where she combines remotely sensed imagery, field interviews, and statistical methods to monitor and forecast land-use dynamics. Dr. Seto cochairs the Urbanization and Global Environmental Change Project of the International Human Dimensions Programme on Global Environmental Change and has served as the remote sensing thematic leader for the International Union for Conservation of Nature's Commission on Ecosystem Management (2002-2008). Dr. Seto is a fellow of the Aldo Leopold Leadership Program (2009), and she is a recipient of the National Science Foundation Faculty Early Career Development Award and the National Aeronautics and Space Administration New Investigator Program in Earth Science Award. She received a B.A. in political science from the University of California at Santa Barbara, an M.A. in international relations and resource and environmental management from Boston University, and a Ph.D. in geography from Boston University.

Dawn J. Wright is a professor of geography in the Department of Geosciences at Oregon State University and holds an adjunct professorship in the College of Oceanic and Atmospheric Sciences. She has authored or co-authored more than 85 articles and five books on marine geographic information systems, marine data modeling, and the hydrothermal activity and tectonics of mid-ocean ridges. Dr. Wright's research currently focuses on coastal/oceanic cyberinfrastructure, geographic information science, benthic terrain and habitat characterization, and the processing and interpretation of high-resolution bathymetry and underwater videography. Additional National Research Council services include the Ocean Studies Board and the Board on Earth Sciences and Resources (BESR) Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research in 2030, as well as the BESR Standing Committee on Geophysical and Environmental Data. Dr. Wright's awards include a National Science Foundation Faculty Early Career Development Award, a Fulbright to Ireland, the Raymond C. Smith Distinguished Alumni Award from the University of California at Santa Barbara, and the Oregon State University Honors College Professor of the Year. In 2007 she was named U.S. Professor of the Year for the state of Oregon by the Carnegie Foundation for the Advancement of Teaching and the Council for the Advancement and Support of Education, and in 2008 a fellow of the American Association for the Advancement of Science. She earned an individual interdisciplinary Ph.D. in physical geography and marine geology from the University of California at Santa Barbara.

National Research Council Staff

Mark D. Lange, *Study Director,* is an associate program officer at the National Research Council's Board on Earth Sciences and Resources and director of the Geographical Sciences Committee. He is a geomorphologist with interests in coastal river processes and geographic information systems. He was a Tyler Environmental Fellow (University of Southern California) and a Knauss Marine Policy Fellow (National Oceanic and Atmospheric Administration) in the U.S. House of Representatives, where he managed environmental and natural resource policy for a member of Congress. He is a member of the Association of American Geographers and the American Geophysical Union and holds a Ph.D. in geography from the University of Southern California.

Jason R. Ortego, *Research Associate*, is with the Board on Earth Sciences and Resources. He received a B.A. in English from Louisiana State University in 2004 and an M.A. in international affairs from George Washington University in 2008. He began working for the National Academies in 2008 with the Board on Energy and Environmental Systems, and in 2009 he joined the Board on Earth Sciences and Resources.

Tonya Fong Yee, *Senior Program Assistant*, is with the Board on Earth Sciences and Resources. She received her B.S. in business administration with a focus on marketing from the University of Florida in Gainesville. Before coming to the National Academies, she interned at the Substance Abuse and Mental Health Services Administration, working on the Safe Schools/Healthy Students Initiative.

Appendix B

Acronyms and Abbreviations

AAG	Association of American Geographers
ALS	amyotrophic lateral sclerosis
CBNRM	community-based natural resources management
CO_2	carbon dioxide
CSISS	Center for Spatially Integrated Social Science
DMSP/OLS	Defense Meteorological Satellite Program, Operational Linescan System
EOC	emergency operations center
EPA	U.S. Environmental Protection Agency
FAO	Food and Agricultural Organization
FEMA	Federal Emergency Management Agency
FRAGSTATS	Spatial Pattern Analysis Program for Categorical Maps
GIS	geographic information system
GMC	genetically modified crop
GPS	Global Positioning System
ICT	information and communication technology
IGERT	Integrative Graduate Education and Research Traineeship (NSF)
IPCC	Intergovernmental Panel on Climate Change
IRB	institutional review board
LBS	location-based service
lidar	light detection and ranging
LRT	light-rail transit
LSC	land-change science
MODIS	Moderate Resolution Imaging Spectroradiometer

NASA	National Aeronautics and Space Administration
NIC	National Intelligence Council
NGS	National Geographic Society
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
OSL	optically stimulated luminescence
PDA	personal digital assistant
QCA	qualitative comparative analysis
SAR	synthetic aperture radar
SoVI	Social Vulnerability Index
STE	science, technology, and engineering
SWOT	Surface Water Ocean Topography
UN	United Nations
USGS	U.S. Geological Survey
UV	ultraviolet
VGI	volunteered geographic information
VMT	vehicle miles traveled

Appendix C

AAG Open Session Agenda and Speakers

Session 3505
National Research Council Study:
Strategic Directions for the Geographical Sciences in the Next Decade

Association of American Geographers Annual Meeting
Fairfield Room
Marriott Copley Place

April 17, 2008
3:10 to 4:50 p.m.

SESSION DESCRIPTION

The National Research Council has undertaken a study entitled *Strategic Directions for the Geographical Sciences in the Next Decade* that will formulate a short list of high-priority research questions in the geographical sciences that are relevant to societal needs. An ad hoc committee has been appointed to carry out this study, and as part of its information-gathering efforts, the committee has invited a group of speakers to present their ideas on the committee's charge. Presenters will be speaking for approximately 10 minutes each, with time at the end for questions and comments.

PRESENTERS

(10 minutes each)
Cindy Fan, University of California, Los Angeles
Laura Pulido, University of Southern California
Patrick Bartlein, University of Oregon
Daniel Sui, Texas A&M University
Eric Sheppard, University of Minnesota
Paul Robbins, University of Arizona
Geoffrey Jacquez, BioMedware

QUESTIONNAIRE

The committee has also developed a questionnaire[1] to allow members of the community to provide input on the committee's task of identifying strategic research questions. The committee will review and consider this input as it deliberates on research questions at subsequent meetings.

Comments received by April 30, 2008, will be considered at the committee's next meeting (May 21-23, 2008). However, the committee welcomes any ideas until August 2008.

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[1] See dels.nas.edu/besr/SD_questionnaire.cgi (accessed March 12, 2010).